The Van Allen Radiation Belts and the RBSP Mission

R. B. Sheldon

NSSTC

Feb10, 2006

The Space Weather Conundrum

(Focussing only on the Outer Belts)

NASA report, 1994

NASA Reference Publication 1390

Spacecraft System Failures and Anomalies Attributed to the Natural Space Environment

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Universities Space Research Association • Huntsville, Alabama

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Marshall Space Flight Center • MSFC, Alabama

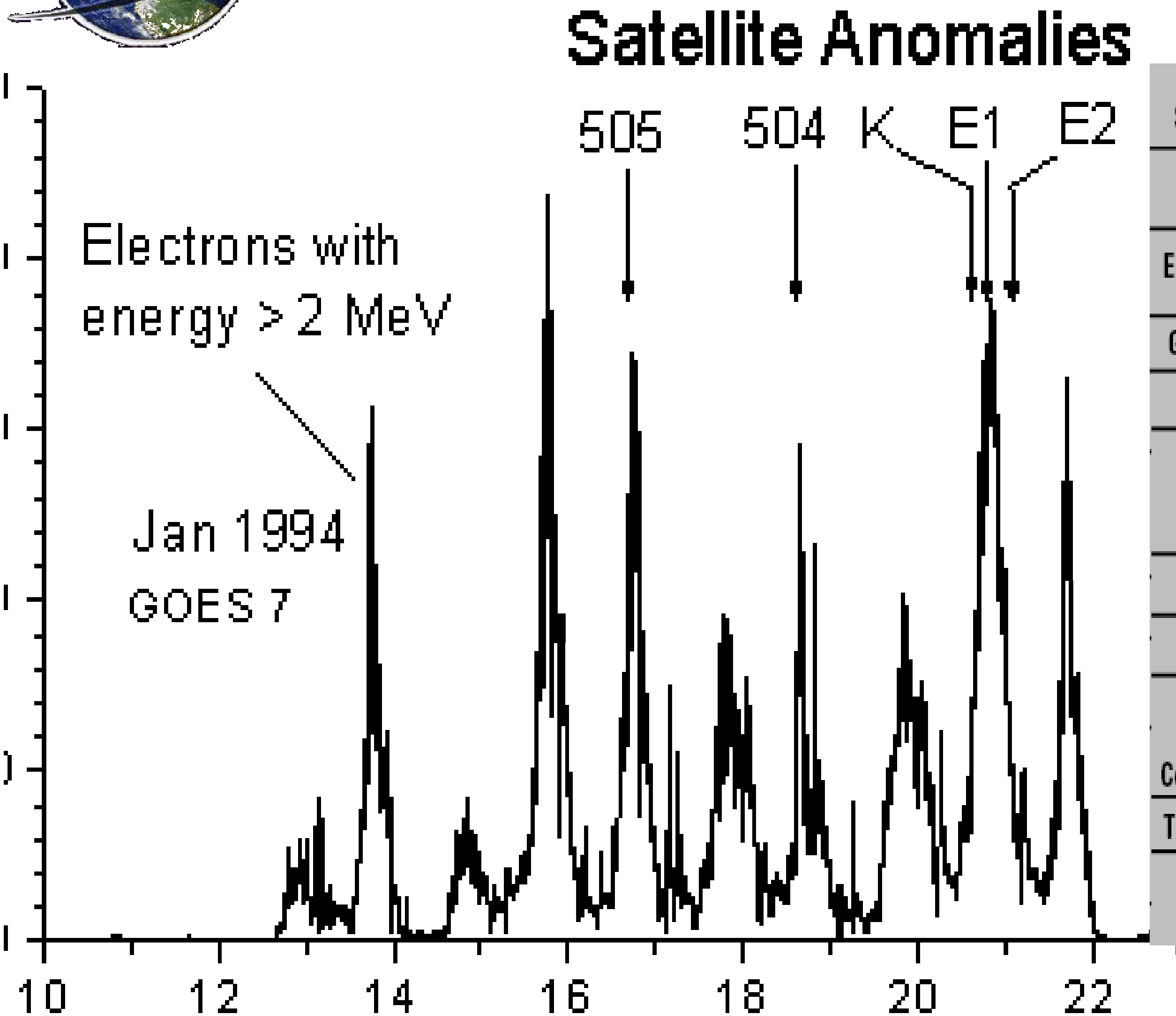
Radiation-caused S/C anomalies

Make	Model	Year	Date	Type
Hughes,	501,Anik,		1994	2MeV Discharging
JAXA	ETS-6	1994	1994	RB damaged solar panel
NASA	STS-61	1992	1992	RB damaged star tracker
NASA	TDRS	All	1993	SEU sensitivity
NASA	EUVE	1992	1993	SEU mode changes
ESA	ERS-1	1991	1992	SEU latchup kills instrument
NASA	CRRES	1990	1991	SEU kills s/c
NASA	HST	1990	1990	SEUs, motor controller etc
ESA	Hipparcos	1989	1993	SEU damage to CPU
NOAA	GOES-7	1987	199	SEU reset
NASA	ERBS	1984	1984ff	SEU damage to RAM
NASA	AMPTE	1984	1989	SEU damage to CPU
	UOSAT-2	1984	1989	SEU
NOAA	GOES-6	1983	1988	SEU damage to CPU
	INSAT-1	1982	1988	SEU upset
NASA	DE-1	1981		

ESTEC Report #11974 1996/NL/JG(SC) Koskinnen et. al.

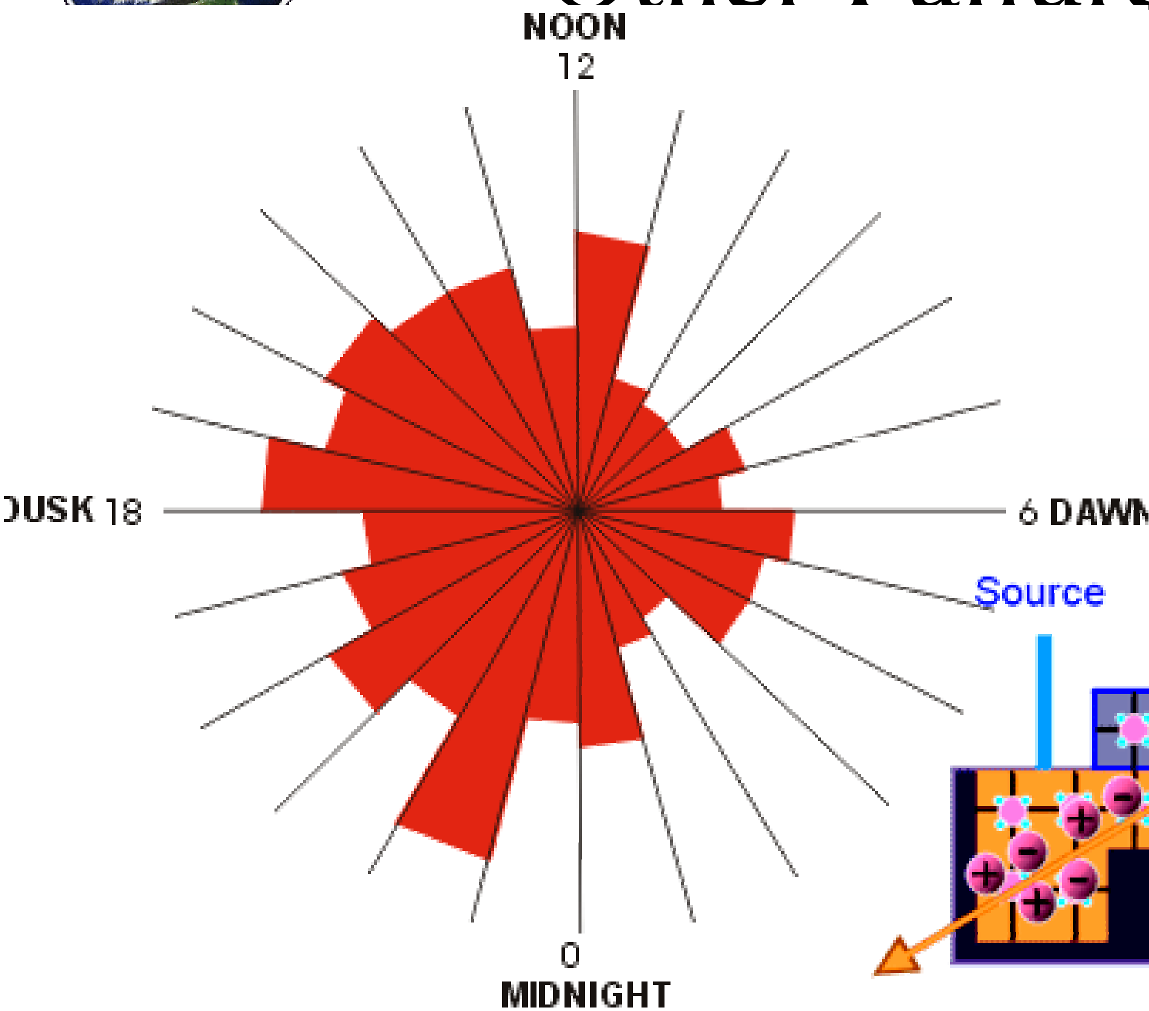
Spacecraft	Time	Comment	Reference
DSP		Anomalies associated with >1.2 MeV electrons	Vampola, 1994
SCATHA		Internal discharges associated with outer radiation belt	Garrett and Whittlesey, 1996
ATS 5 and ATS 6		Charged to 10 kV in eclipse at GEO	SMASS Report
NOAA spacecraft	from 1971	Contains 2779 events from 1971to 1988	Wilkinson, 1994
Goddard spacecraft	1993-1995	More than 400 anomalies	Remez and McLeod, 1996; Walter, 1995
Voyager 1		Power-on resets	Leung et al., 1986
Pioneer		Severe space weather near Jupiter	SMASS Report
GPS		Clock shift, false commands	James et al., 1994
Intelsat 3 and 4		Spin up	James et al., 1994
GOES 2			Lauriente et al., , 1996, 1998
GOES 3		Upsets	
GOES 4	Nov 26, 1982	Instrument failed on arrival of 110-500 MeV protons	Vampola 1994
Intelsat K	Jan 20 1994	Loss of attitude control in GEO	Baker et al. 1994
ANIK E1 and ANIK E2	Jan 20-21 1994	Loss of attitude control due to high energy electrons	Baker et al. 1996
ANIK E1	Mar 26 1996	Array of solar power panels disconnected	ISTP Newsletter, Vol 6, no 2, 1996.
DRA-delta		Phantom commands	Wrenn and Sims, 1996
CTS		Short circuit	James et al., 1994
DSCS II		Spin up, amplifier gain	James et al., 1994
DMSP 7		Charged to 300 V in less than a second- associated with a sharp drop in ion density	Stevens and Jones, 1995
GOES 5	July 22 1984	Failure during high energetic electron fluxes	Baker
DMSP F13		Problems while passing through an aurora	Anderson and Koons, 1996
Hispasat 1A and 1B	Sep 1992 and July 1993		Selding, 1998
Telstar 401	Jan 11 1997	Failure probably due to coronal mass ejection	Anselmo, 1997
Telstar 402		Spacecraft charging	Lanzerotti et al., 1996
Topex/Poseidon		Failures due to electrostatic discharges and SEUs caused by high energy protons	Lauriente and Vampola 1996
Intelsat 511	Oct 7 1995	Lost Earth lock	http://www.astro.lu.se/~henrik/spacew4b.html
GOES 8	Feb 14 1995	Attitude control difficulty	http://www.astro.lu.se/~henrik/spacew4b.html
TDRSS 1	1988-1991	SEUs anticorrelated with solar cycle	Wilkinson 1994
CRRES	1990	674 reported anomalies	Violet & Frederickson 1993
Tempo 2	11 Apr 1997	Temporary power fluctuations.	http://www.seds.or

Internal Discharge 1/1994

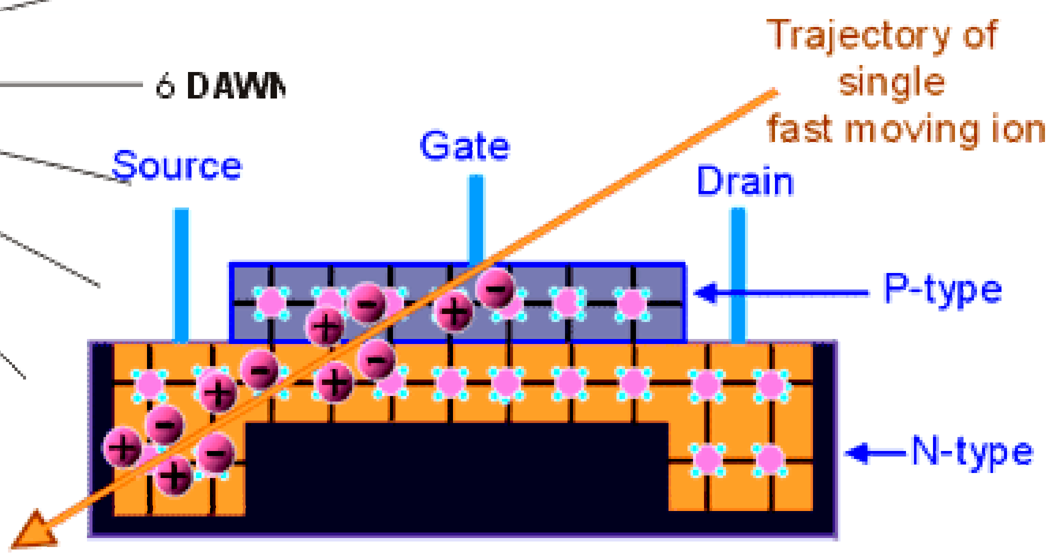


SPACECRAFT SUBSYSTEMS	Ionizing Radiation
Avionics	Degradation: SEU's, Bit Errors, Bit Switching
Electrical Power	Decrease in Solar Cell Output
GN&C/Pointing	
Materials	Degradation of Materials
Optics	Darkening of Windows and Fiber Optics
Propulsion	
Structures	
Telemetry, Tracking, & Communications	
Thermal Control	
Mission Operations	Crew Replacement Timelines

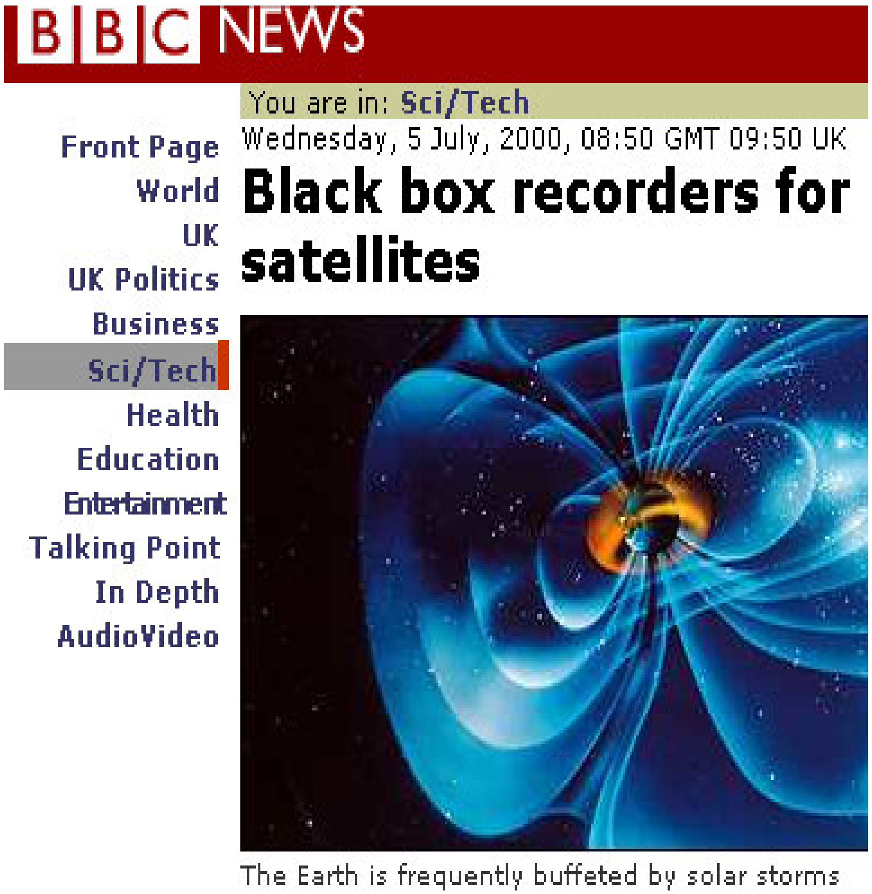
Other Failure modes



Local time distribution of occurrences of static discharges, based on 122 reported events.
Radial extent shows relative number of events in each sector.
After Lam and Hruska, 1991, J. Spacecraft and Rockets



BBC News 6/5/2000


BBC NEWS

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UK Politics
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Sci/Tech
Health
Education
Entertainment
Talking Point
In Depth
AudioVideo

Wednesday, 5 July, 2000, 08:50 GMT 09:50 UK

Black box recorders for satellites

The Earth is frequently buffeted by solar storms

- Space satellites are to get black box recorders which store the details of the moments leading up to disasters. The project is driven by the massive losses in the space insurance industry. Companies lost \$850m in 1998, after paying out \$1.9bn in claims. …The project's leader. Dr Andrew Coates, told BBC News Online that the device would measure the flow of the high energy particles flying through space.

Galaxy 4 Failed May 1998 Blanked out 90% of US pagers ~\$160m

Telstar 401 Failed January 1997TV stations go off-air ~\$200m

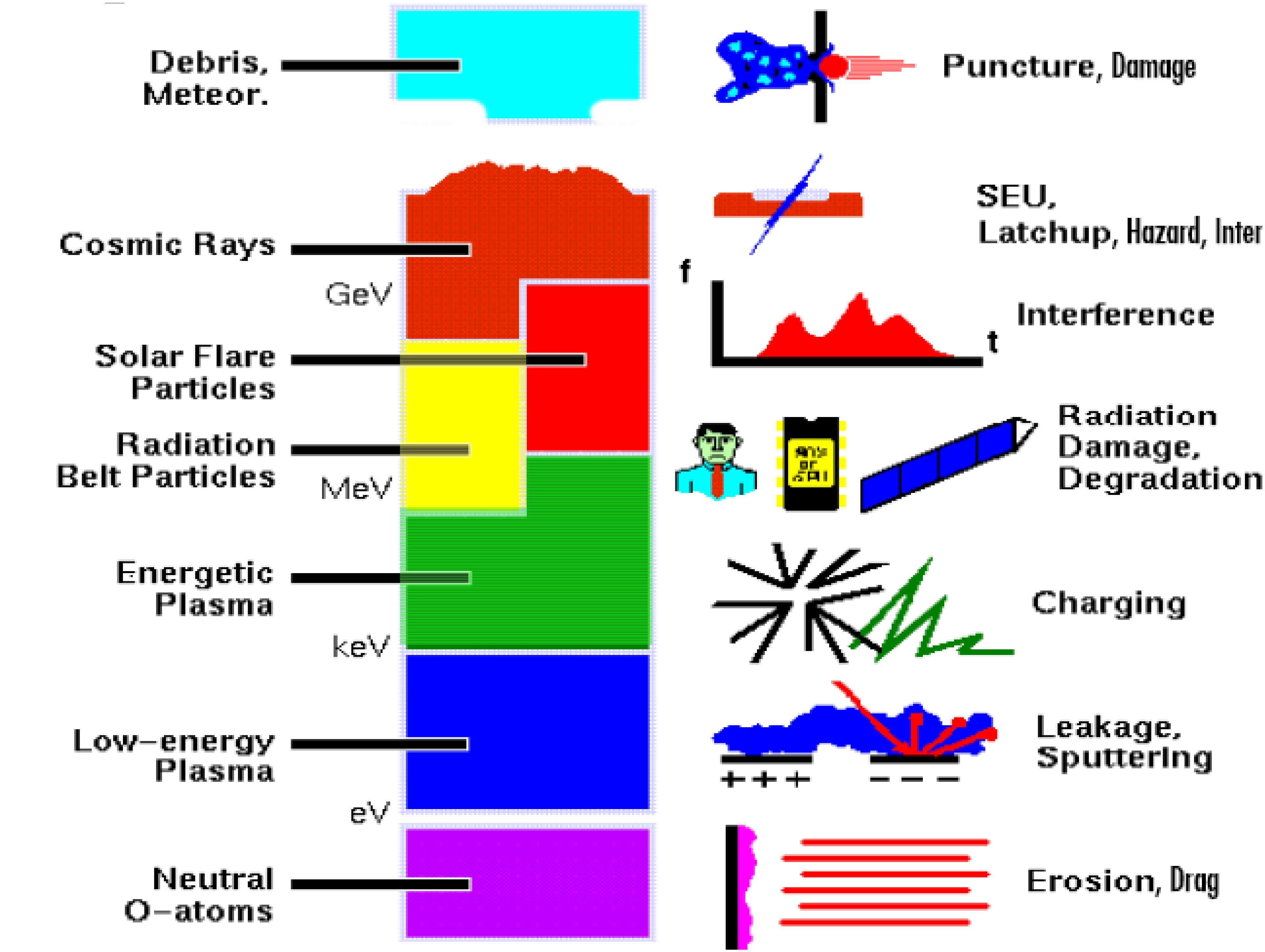
ESA report, Daly 2002

Space environments and effects analysis section

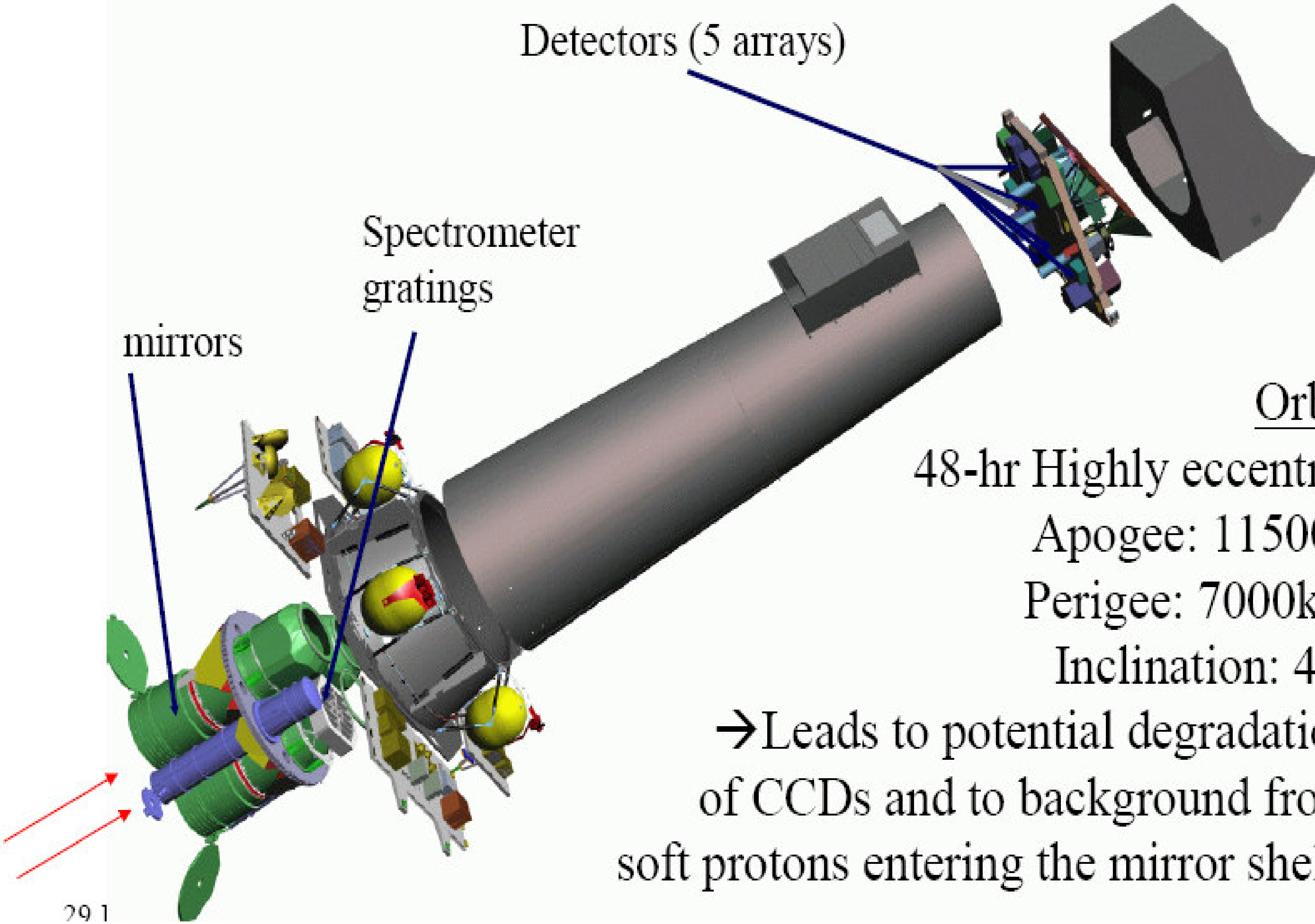
Effects on Technology

Éamonn Daly

ESA Space Environments and Effects Analysis Section
Noordwijk
The Netherlands


Debris, Meteor.
Cosmic Rays
GeV
Solar Flare Particles
Radiation Belt Particles
MeV
Energetic Plasma
keV
Low-energy Plasma
eV
Neutral O-atoms
Puncture, Damage
SEU, Latchup, Hazard, Inter
f
t
Interference
Radiation Damage, Degradation
Charging
Leakage, Sputtering
+ + +
− − −
Erosion, Drag

XMM: Radiation Damage to Detectors

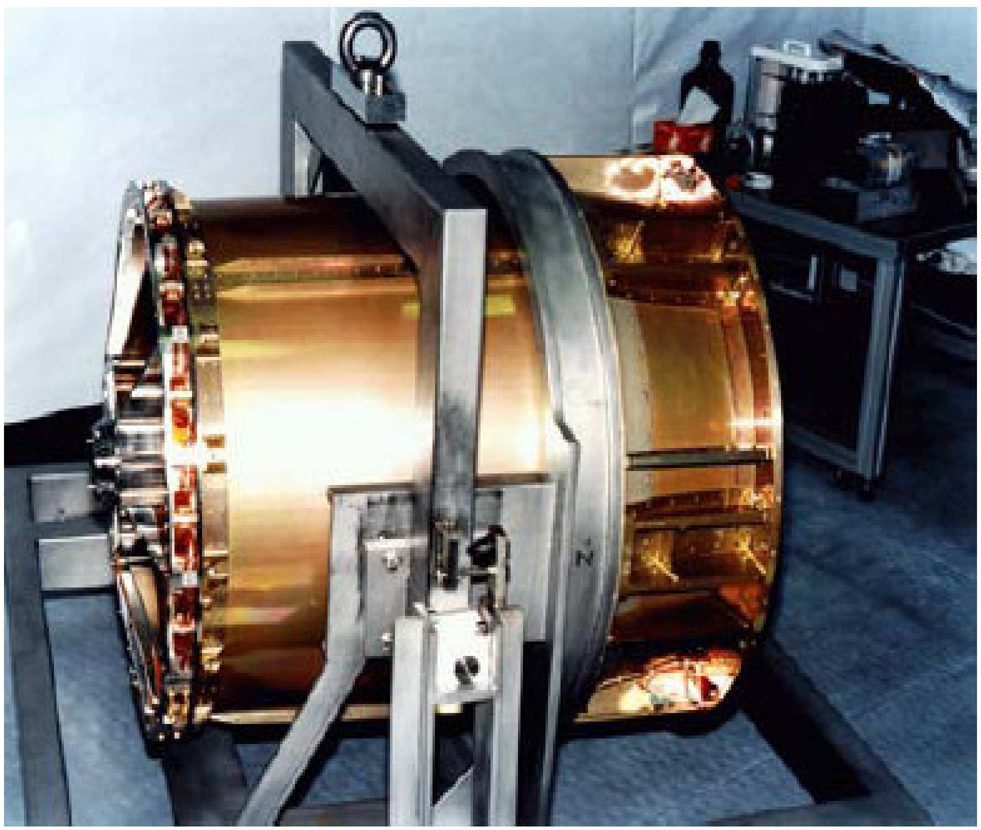


Orbit

48-hr Highly eccentric
Apogee: 115000
Perigee: 7000km
Inclination: 40°
→Leads to potential degradation of CCDs and to background from soft protons entering the mirror shells

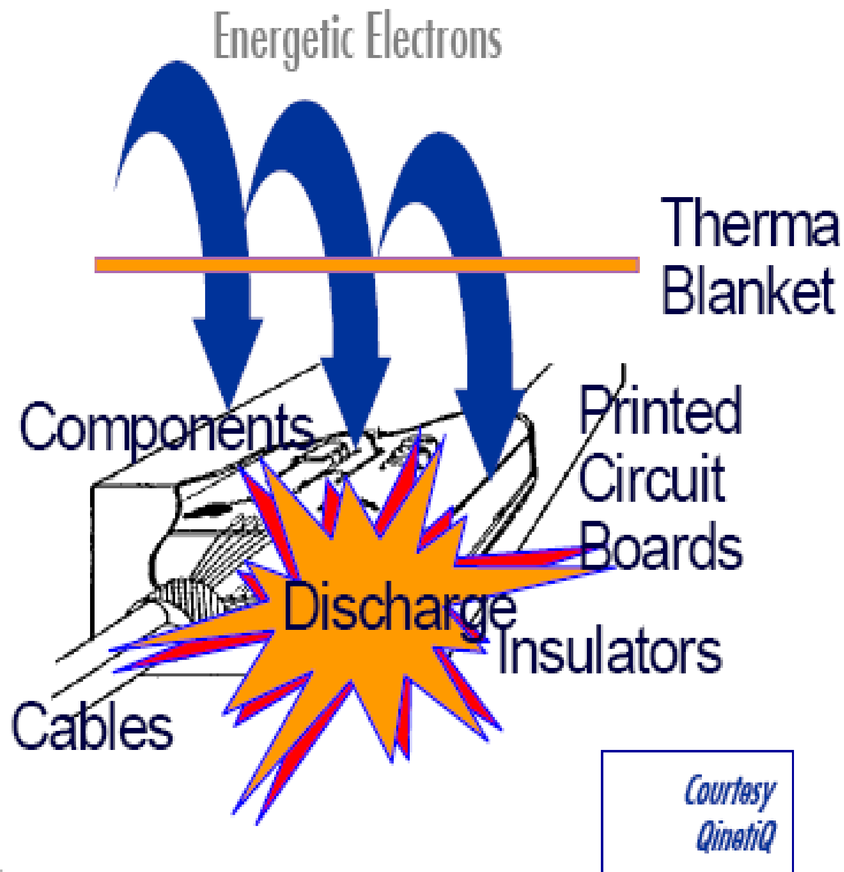
Mirror Module of XMM:

- 58 shells with mm-sized gaps

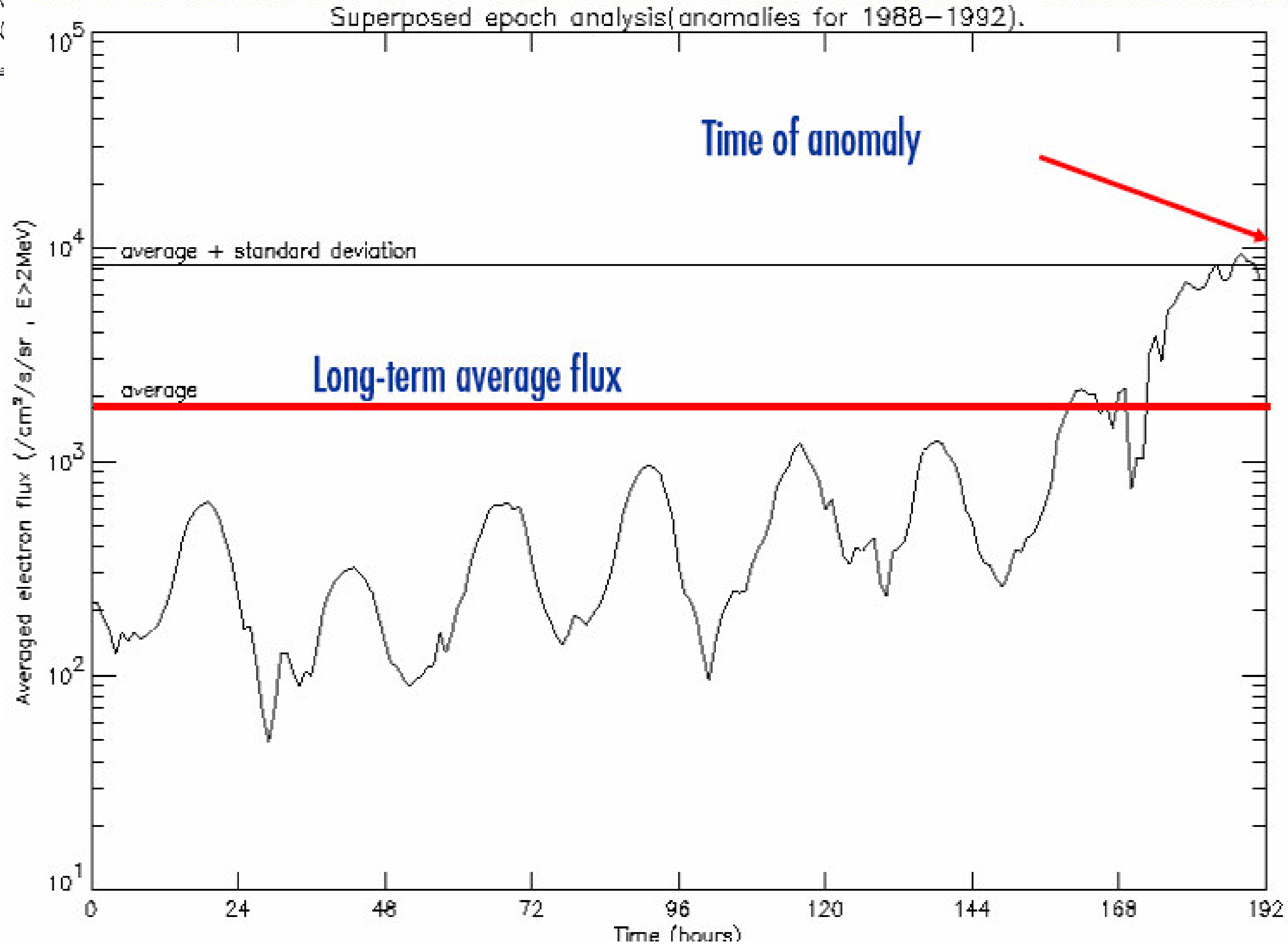


Spacecraft Charging

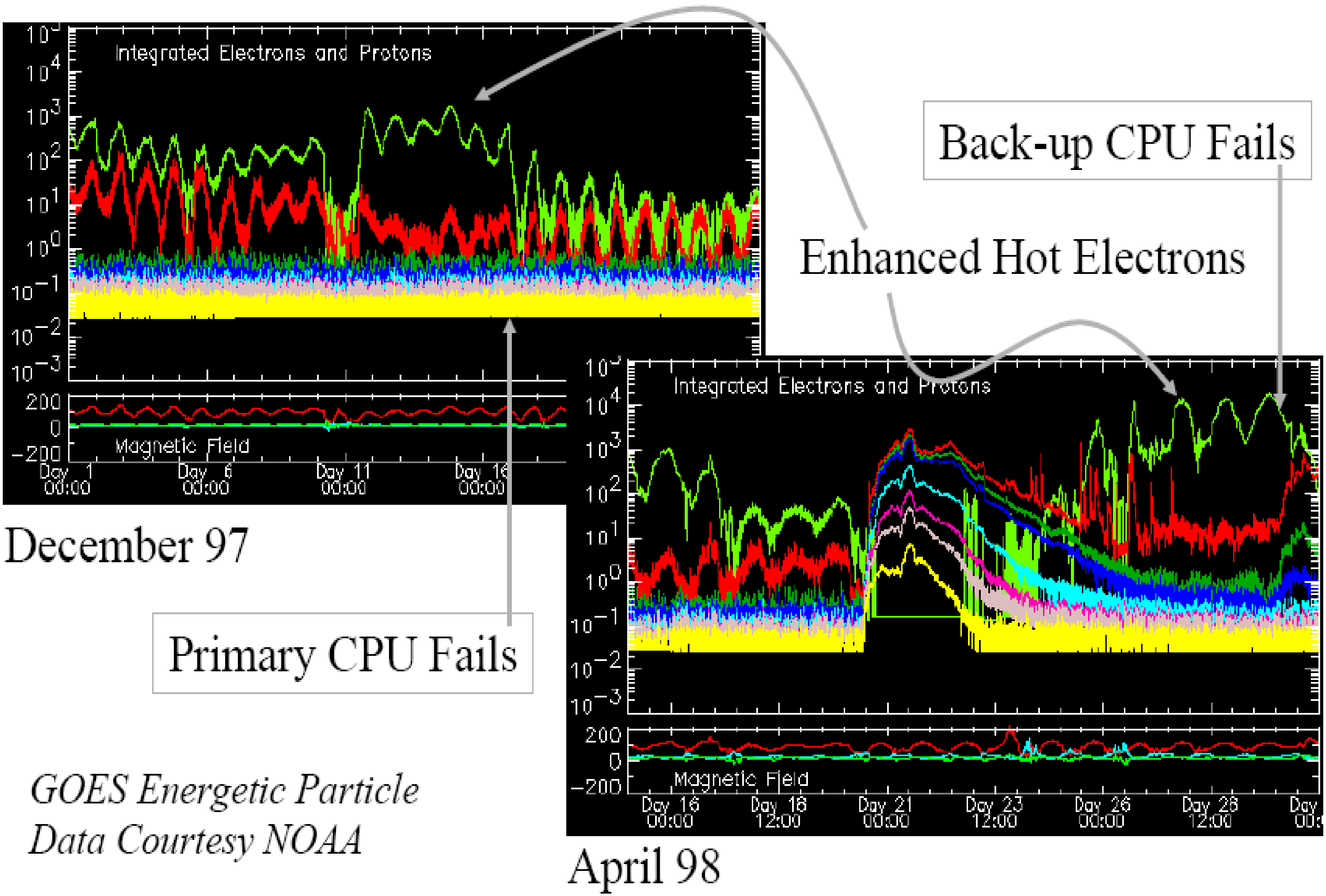
- Many satellites experience "anomalies" which do not lead to satellite loss
- e.g. ESA satellites Marecs, ECS, and Meteosat in 1980's-90's
- ANIK-E1 & E2 failures in 94 & 96
- (Telstar 401 failure on 10th Jan 1997 following CME on 7th - not charging?
- Galaxy4 satellite anomaly led to pager network outage - not charging?)
- For service providers, price of inadequate hardening can be loss of spacecraft and expensive compensation / litigation
- To protect is also expensive as shielding mass is costly



Behaviour of Average Energetic Electron Flux before a Meteosat Status Anomaly



Equator-S Failure



GOES Energetic Particle
Data Courtesy NOAA

P-ANIK!

High-tech chaos as satellites spin out of control

Plug pulled on phones, TV, radio, papers

The New York Times

2 Canadian Space Satellites Are Knocked Out by Storm

OTTAWA, Jan. 22 (Reuters) — An electromagnetic storm knocked out Canada's two communications satellites Thursday, and one of them may be lost for ever, the operating company, Telesat Canada, said Friday.

Telesat executives said an unusual localized storm caused short-circuits on its Anik E-1 and E-2 satellites, disrupting telephone, television and transmission s

EOS

Developing Service Promises Accurate Space Weather Forecasts in the Future

Science & Medicine

Weathering the storm in space

The Globe and Mail, Tuesday, January 25, 1994

REPORT ON BUSINESS

Sun gets blame for zapped Aniks

Telesat still trying to fix $300-million satellite, but chance of revival dim

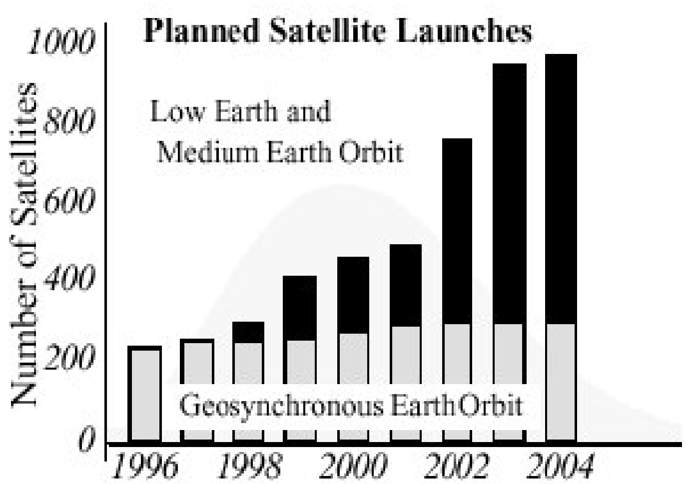
Image Credit: L. J. Lanzerotti, Bell Laboratories, Lecent Technologies, Inc.

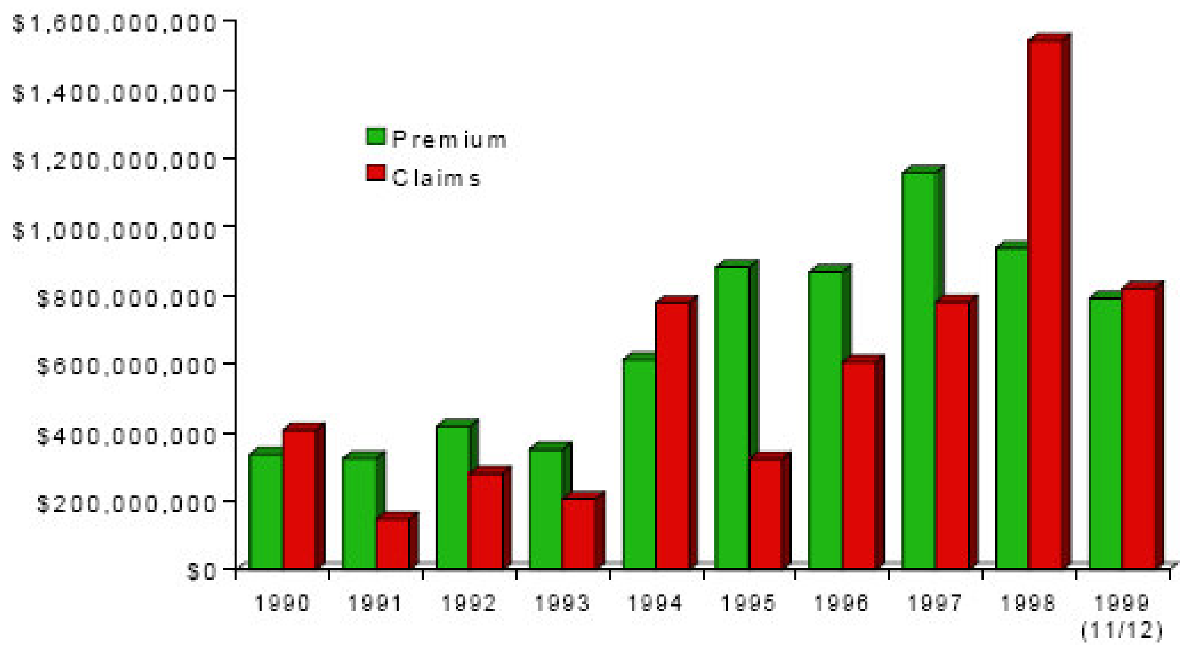
Bad years are getting worse…

Assets in Space - Satellite Insurance

- Total value of more than 600 satellites currently in orbit is about $50-100 billion
  - 235 of these are insured (value: $20 billion)

- Growing market: 1500 space payloads are expected to be launched the next 10 years
  - potential insured value $80 billion





Near Real-Time Data

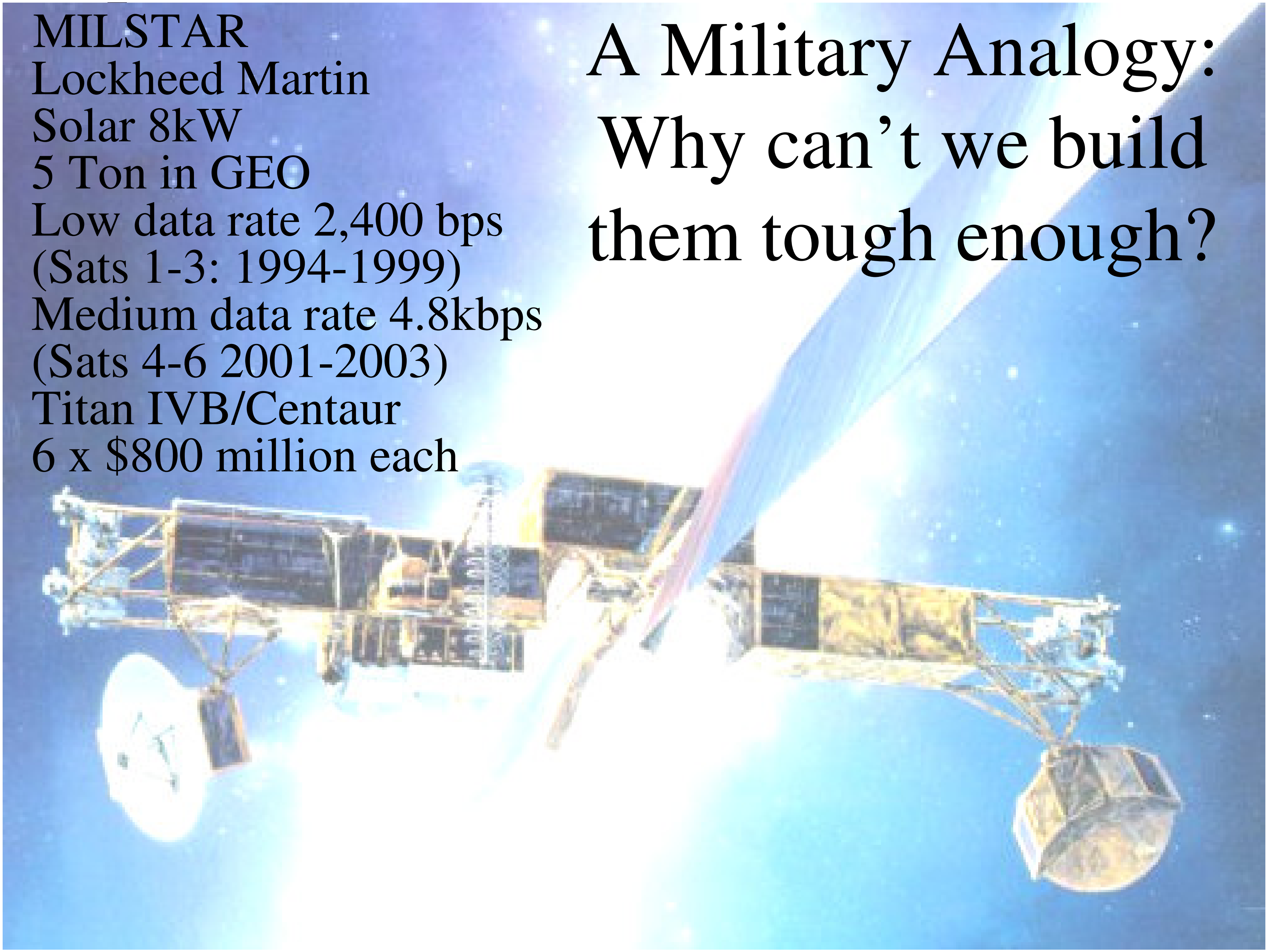
Component	Available Measurement	Caveat	Delay before availability
Radiation belts proton energy spectrum 1 MeV to 1 GeV	GOES NPOES	Only at GEO Reduced energy range Only at 830 km	5 min 1 hour
Radiation belts electrons energy spectrum 100 keV to 10 MeV	GOES LANL NPOES Kp A	Only at GEO Only at GEO Only at 830 km Proxy Proxy	5 min 24 hours 1 hour 1 day 1 day

Forecast: Precursor

Phenomenon	Tracer	Precursor
Flare	X, UV, Vis, MeV protons	Sunspot Magnetic structure
CME	Vis image	Sunspot
ICME	Radio Interplanetary scintillation	CME
SPE	MeV protons	CME
Substorm	AE, Kp NPOES	
Storm	Kp GOES LANL	IMF Bz <0
Ionospheric and thermospheric change	TEC Radars	EUV from backside IMF Bz <0

A Military Analogy: Why can’t we build them tough enough?

MILSTAR
Lockheed Martin
Solar 8kW
5 Ton in GEO
Low data rate 2,400 bps
(Sats 1-3: 1994-1999)
Medium data rate 4.8kbps
(Sats 4-6 2001-2003)
Titan IVB/Centaur
6 x $800 million each



2005 Sten Odenwald's Space Weather site: Factoids

The global satellite industry is worth $104.6 billion in 2004.

There were 37 satellites launched into space in 2004.

The most expensive unmanned satellite is the HST at $2.5bn

In 2004 eight satellites burned-up in the atmosphere

The longest living satellite is the 28yr old ATS-3 still in service in 2000

The most massive satellite launched: Compton Gamma Ray Observatory (15,713 kg)

The most power-hungry satellite is NSS-8 requiring 14kW

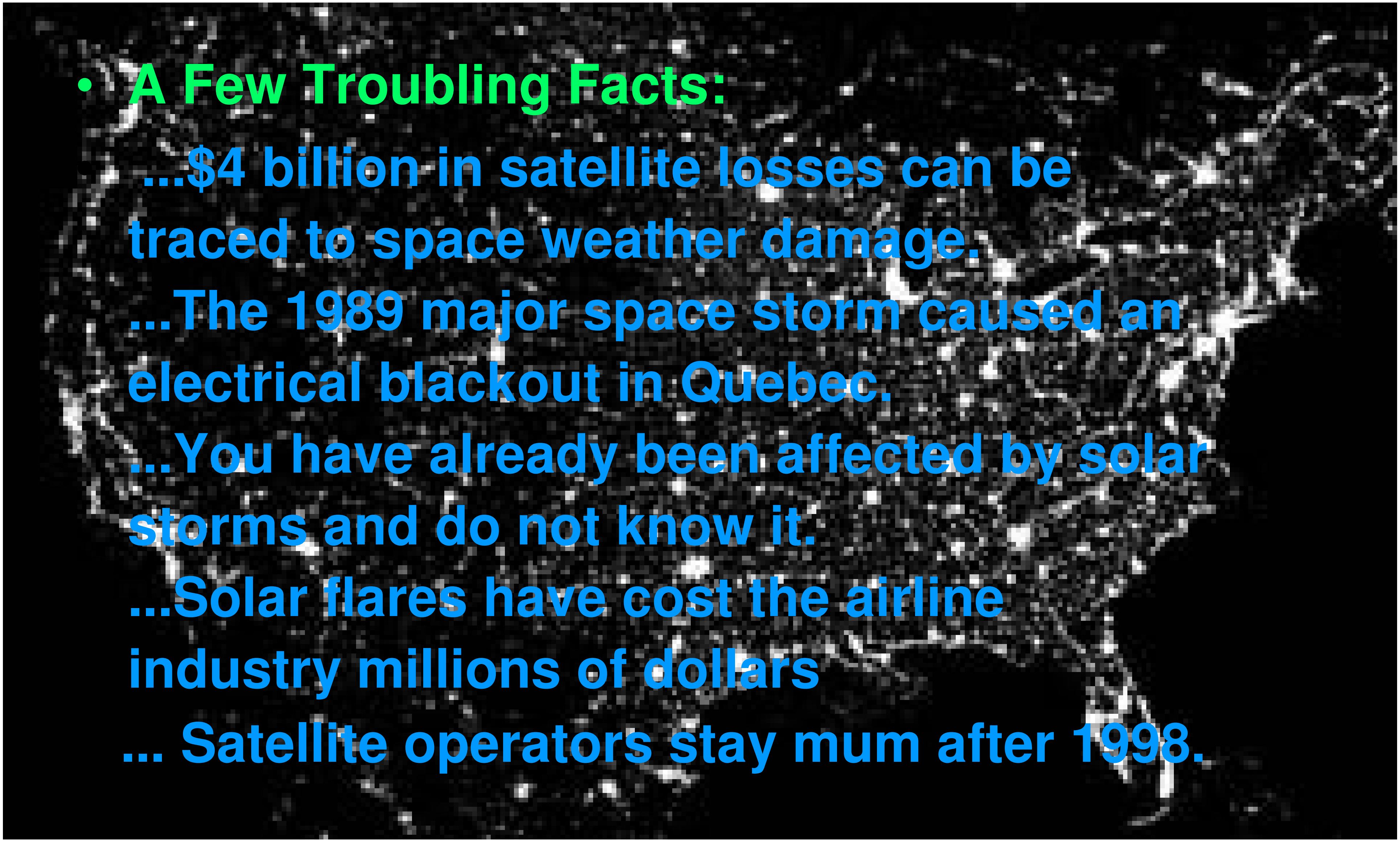
In 2005, 3,102 TV programs were broadcast by satellites

There are 500,000 VSAT satellite internet users worldwide.

There are a total of 367 GEO sats operating in space in 2004.

Military sats can see details on Earth's only 10cm across.

Sten’s Preparedness Index: Fair



- A Few Troubling Facts:

...$4 billion in satellite losses can be traced to space weather damage.

...The 1989 major space storm caused an electrical blackout in Quebec.

...You have already been affected by solar storms and do not know it.

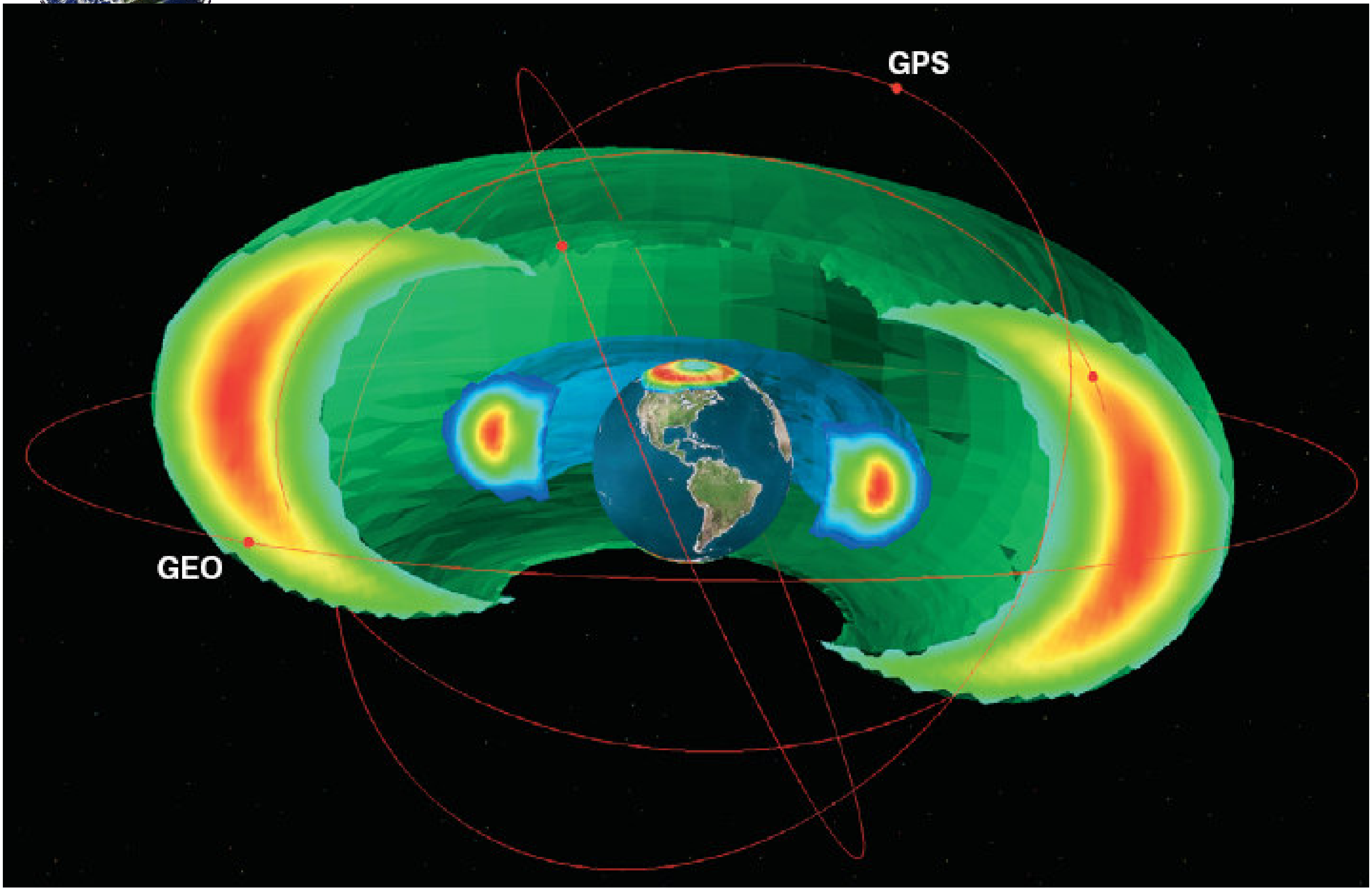
...Solar flares have cost the airline industry millions of dollars

... Satellite operators stay mum after 1998.

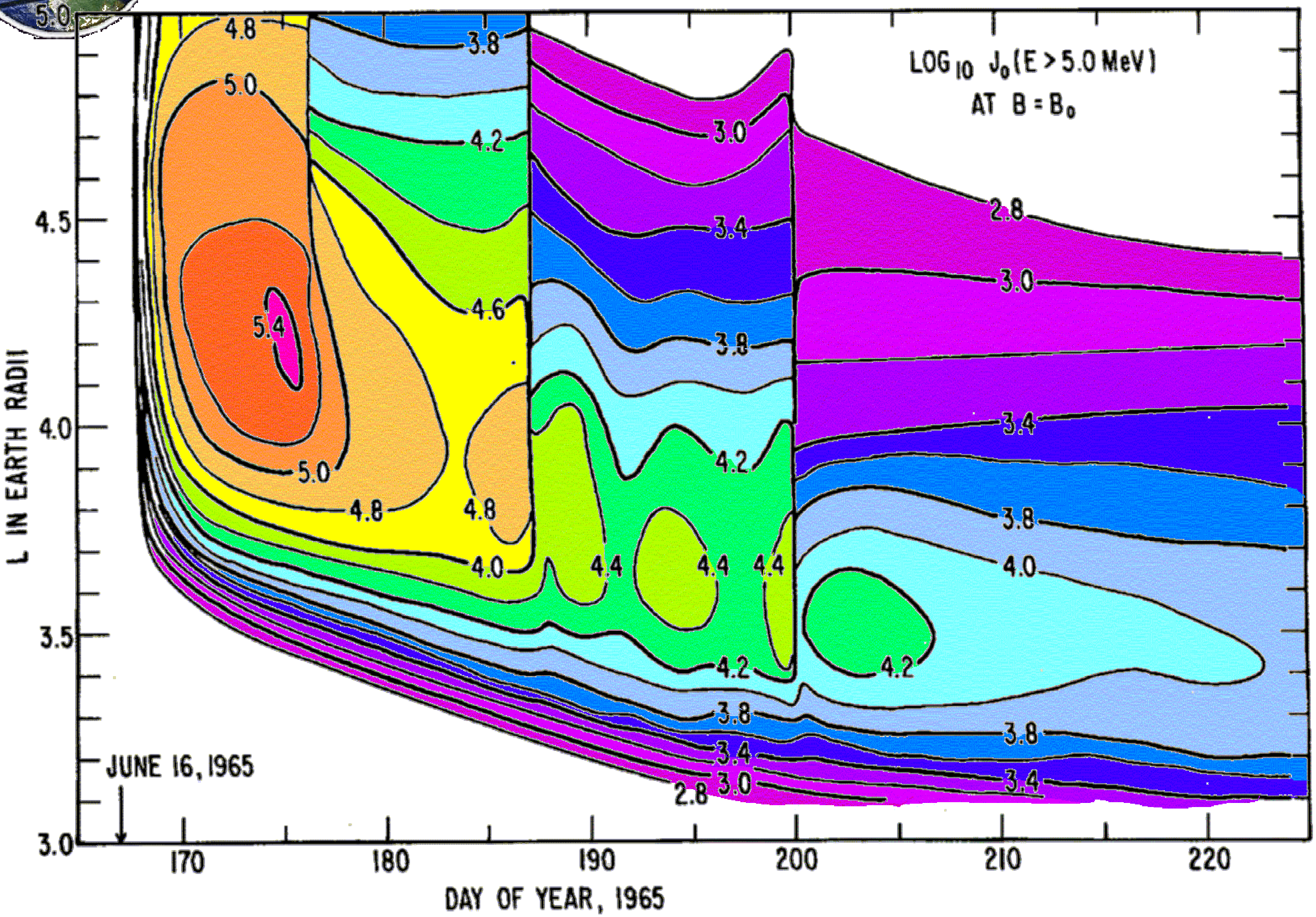
The Outer Van Allen Radiation Belt

Just the electrons, Ma'am, nothing but the electrons.

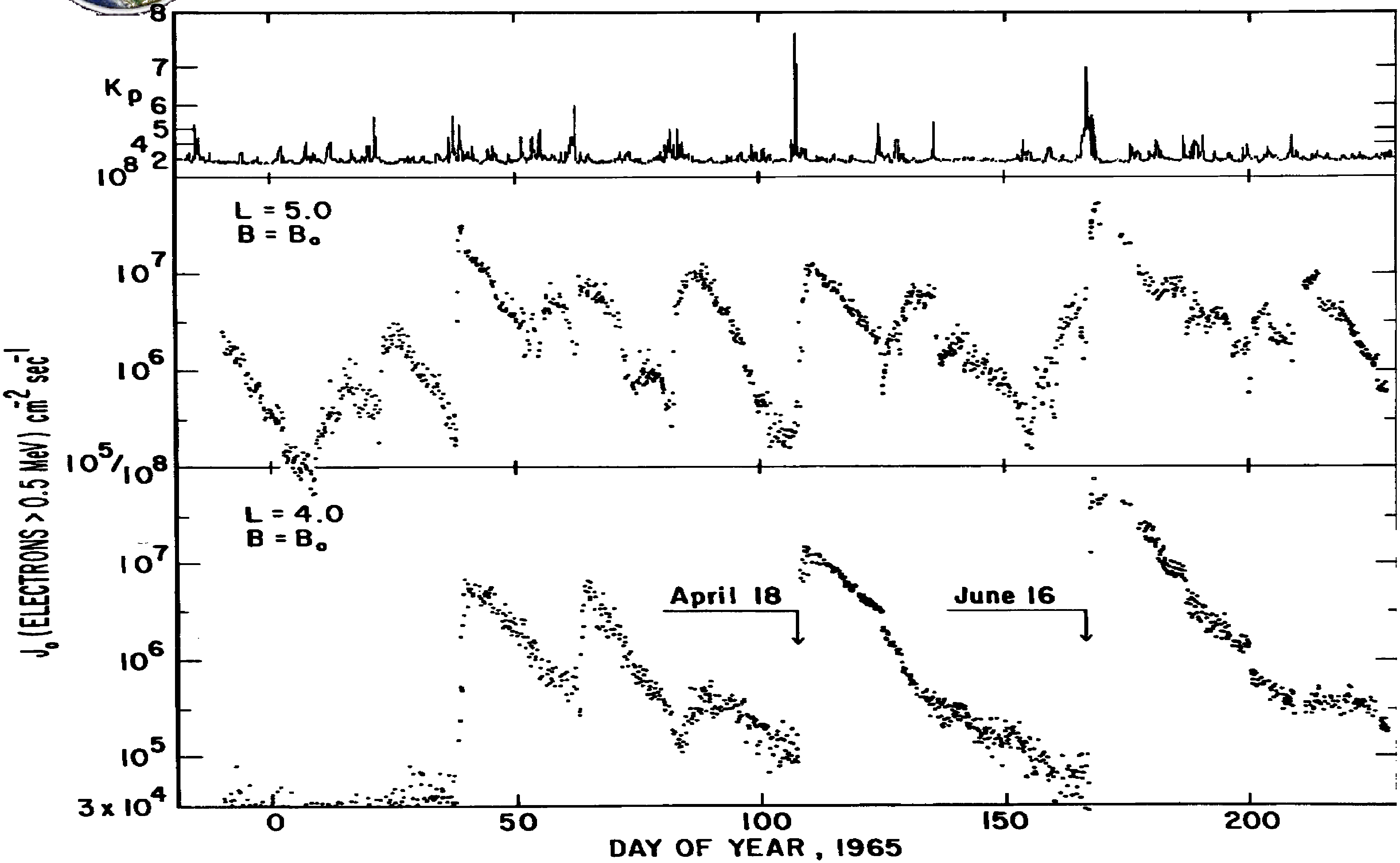
Inner and Outer Van Allen Belts



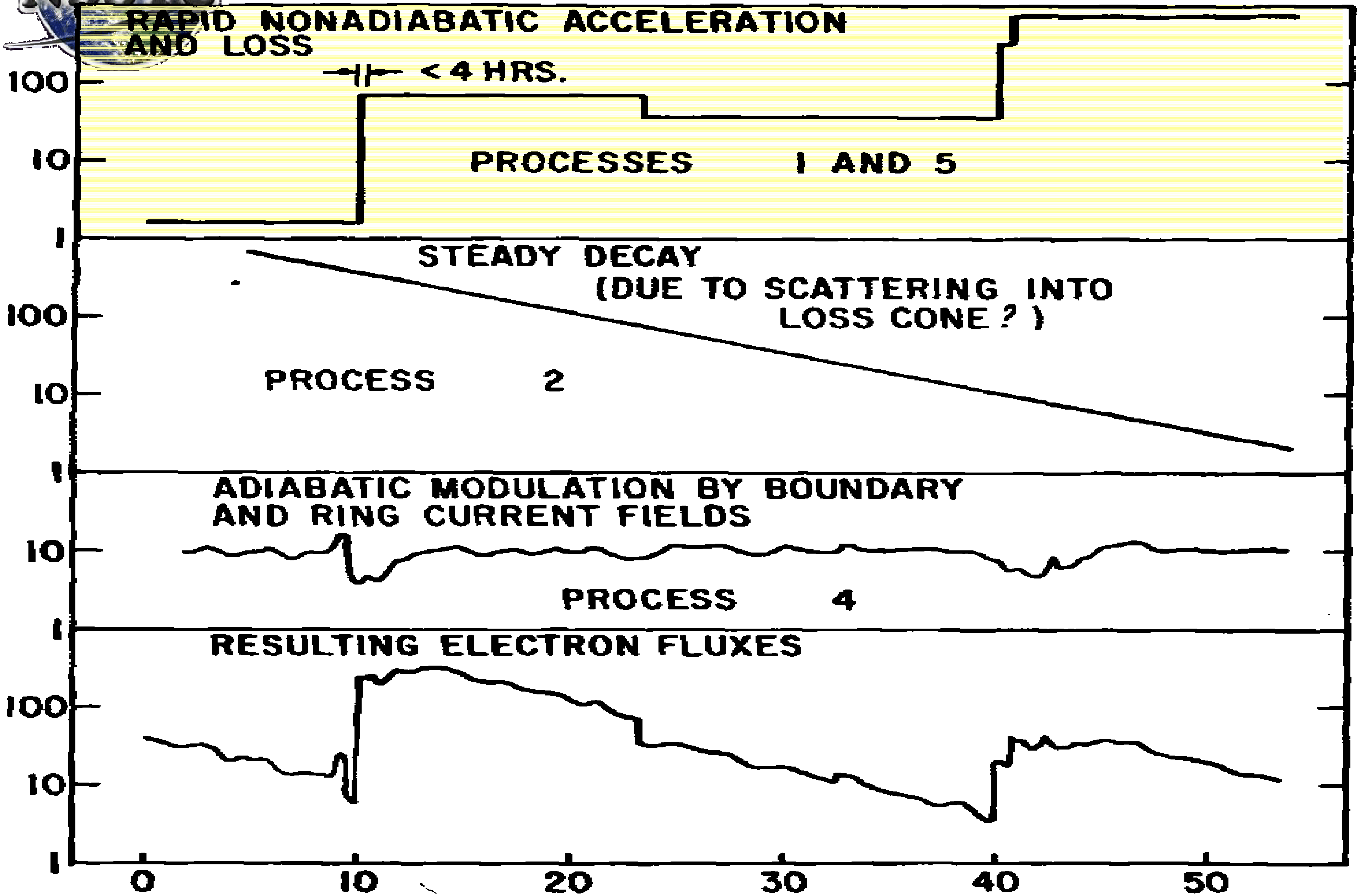
McIlwain, 1966

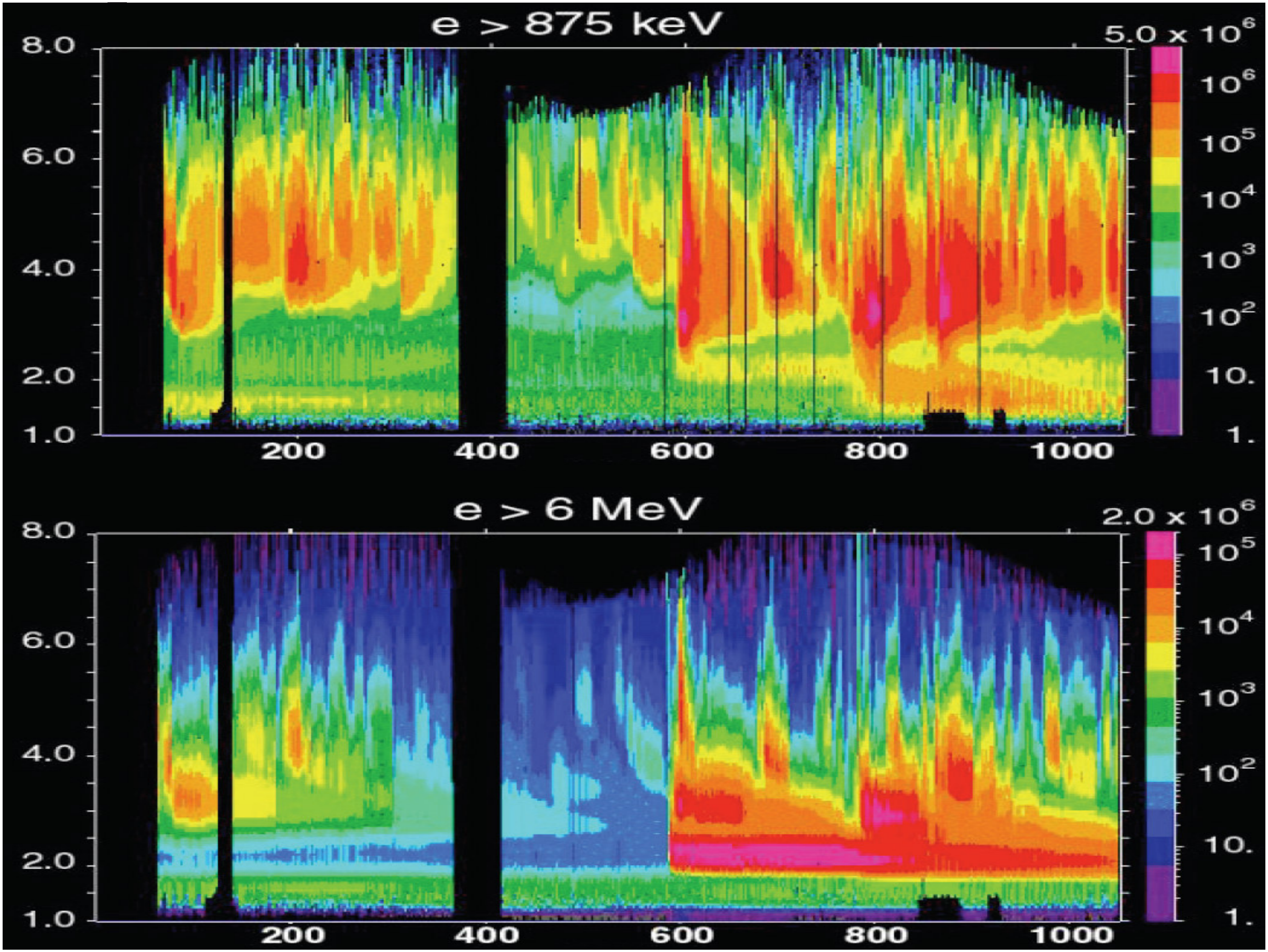


ORBE (McIlwain 1966)

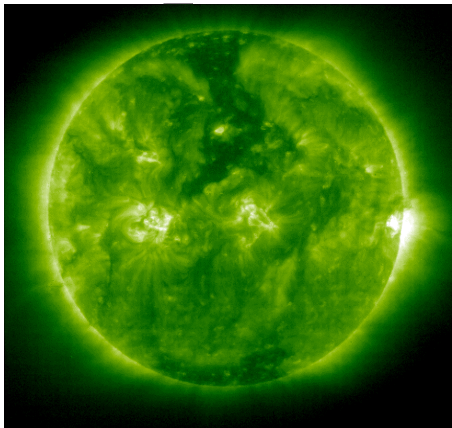


McIlwain 1966

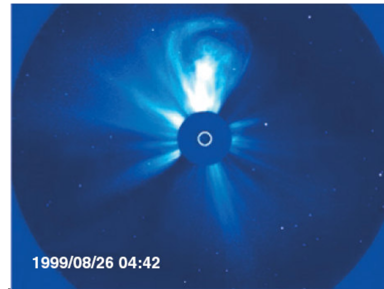


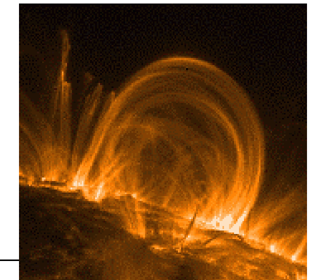


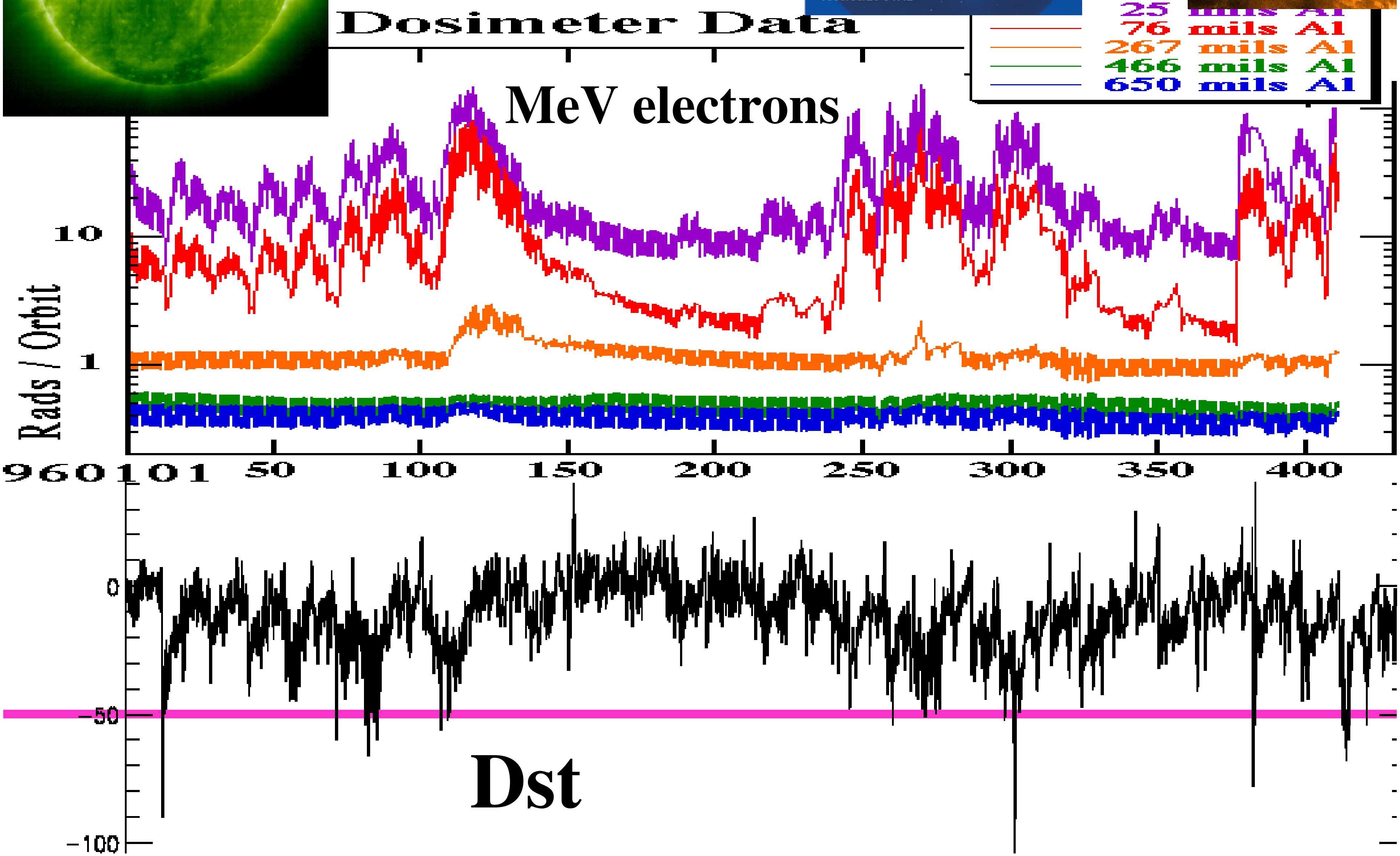
e > 875 keV
5.0 x 10^6
8.0
6.0
4.0
2.0
1.0
200
400
600
800
1000
10^6
10^5
10^4
10^3
10^2
10.
1.
e > 6 MeV
2.0 x 10^6
10^5
10^4
10^3
10^2
10.
1.



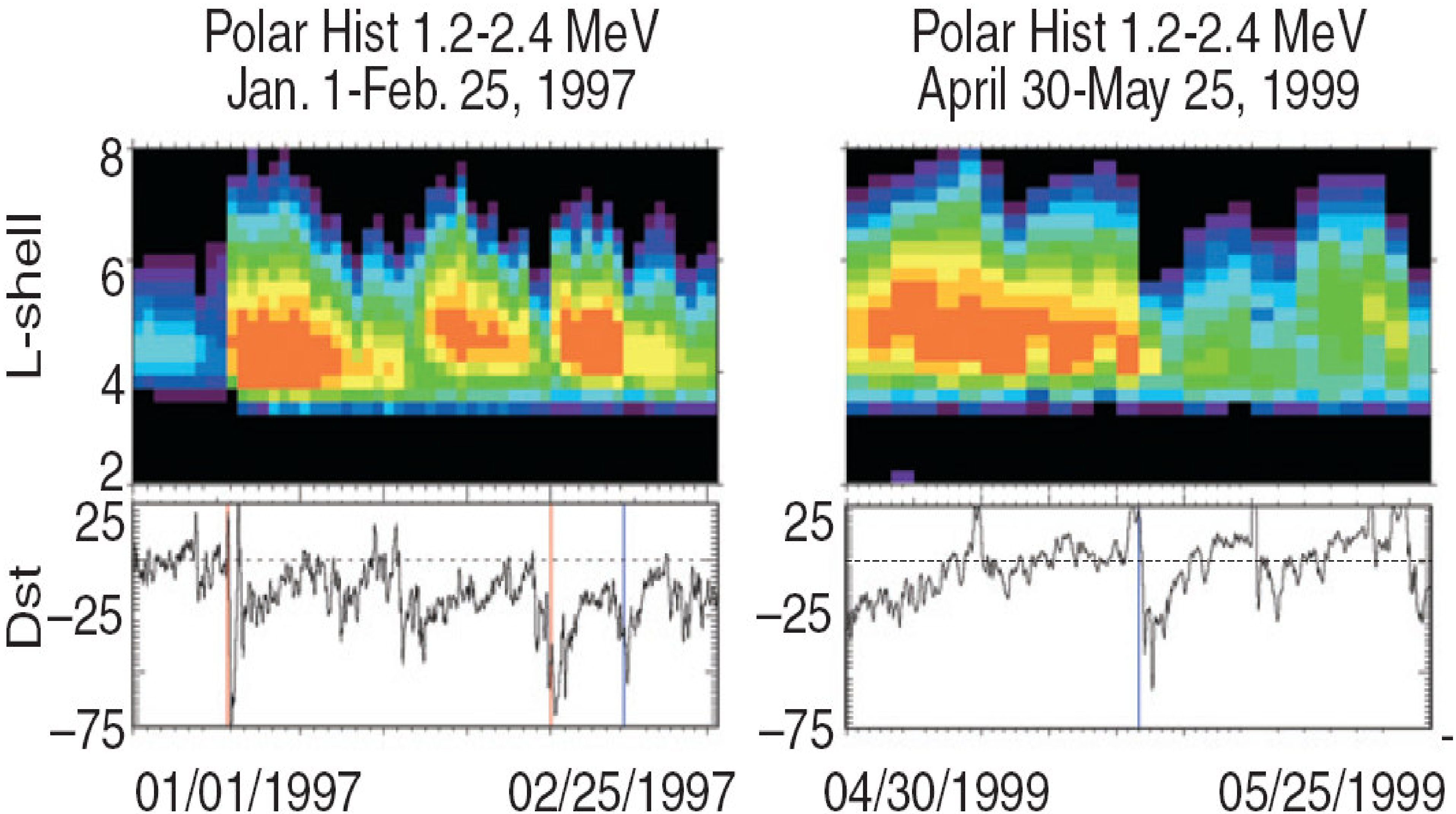
1996

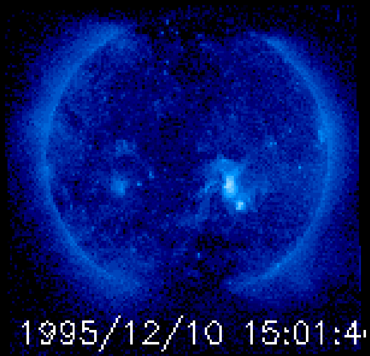

1999/08/26 04:42




Dosimeter Data
MeV electrons
25 mils Al
76 mils Al
267 mils Al
466 mils Al
650 mils Al
Rads / Orbit
10
1
960101
50
100
150
200
250
300
350
400
0
−50
−100
Dst

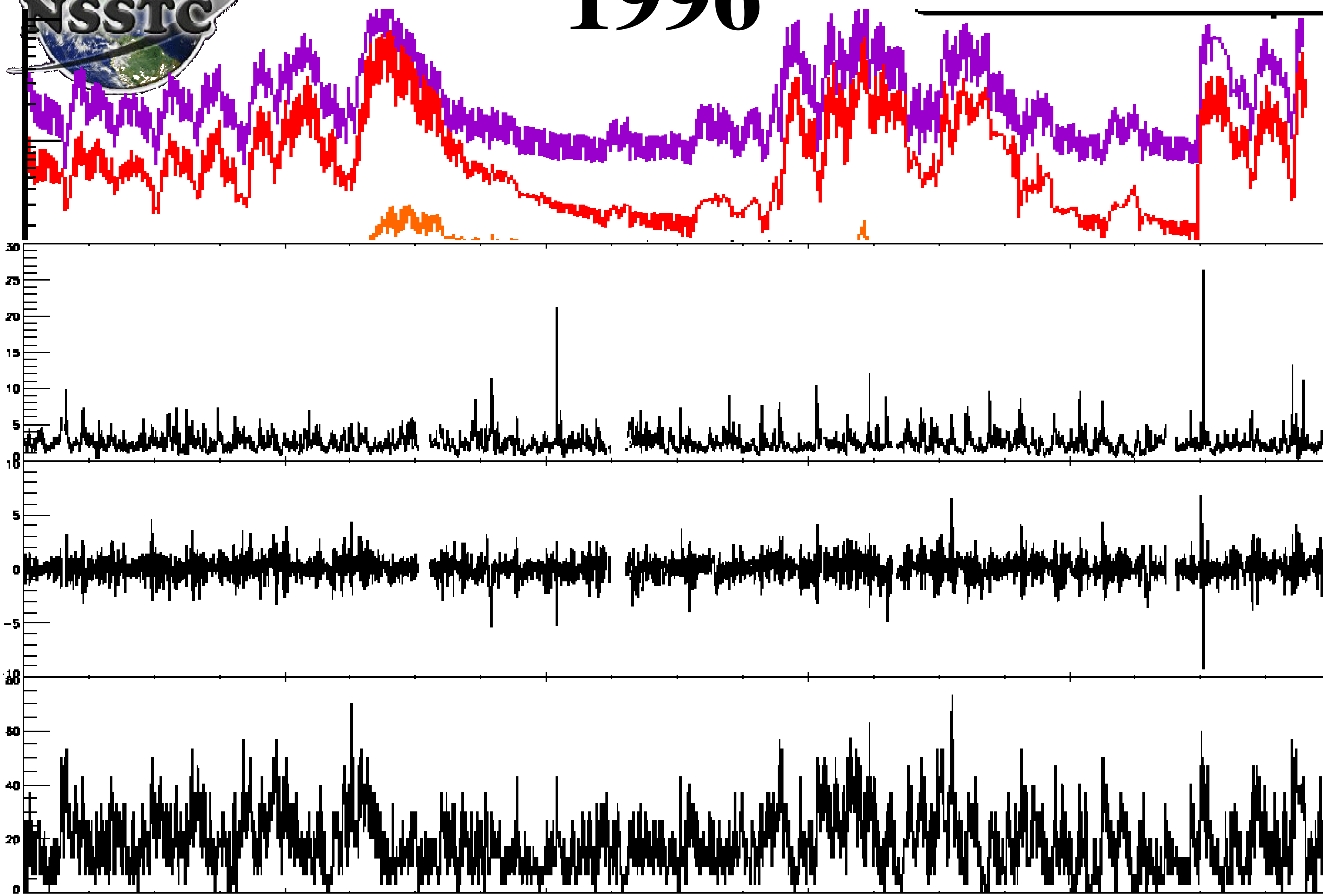
Dst correlated & anti-correlated with ORBE



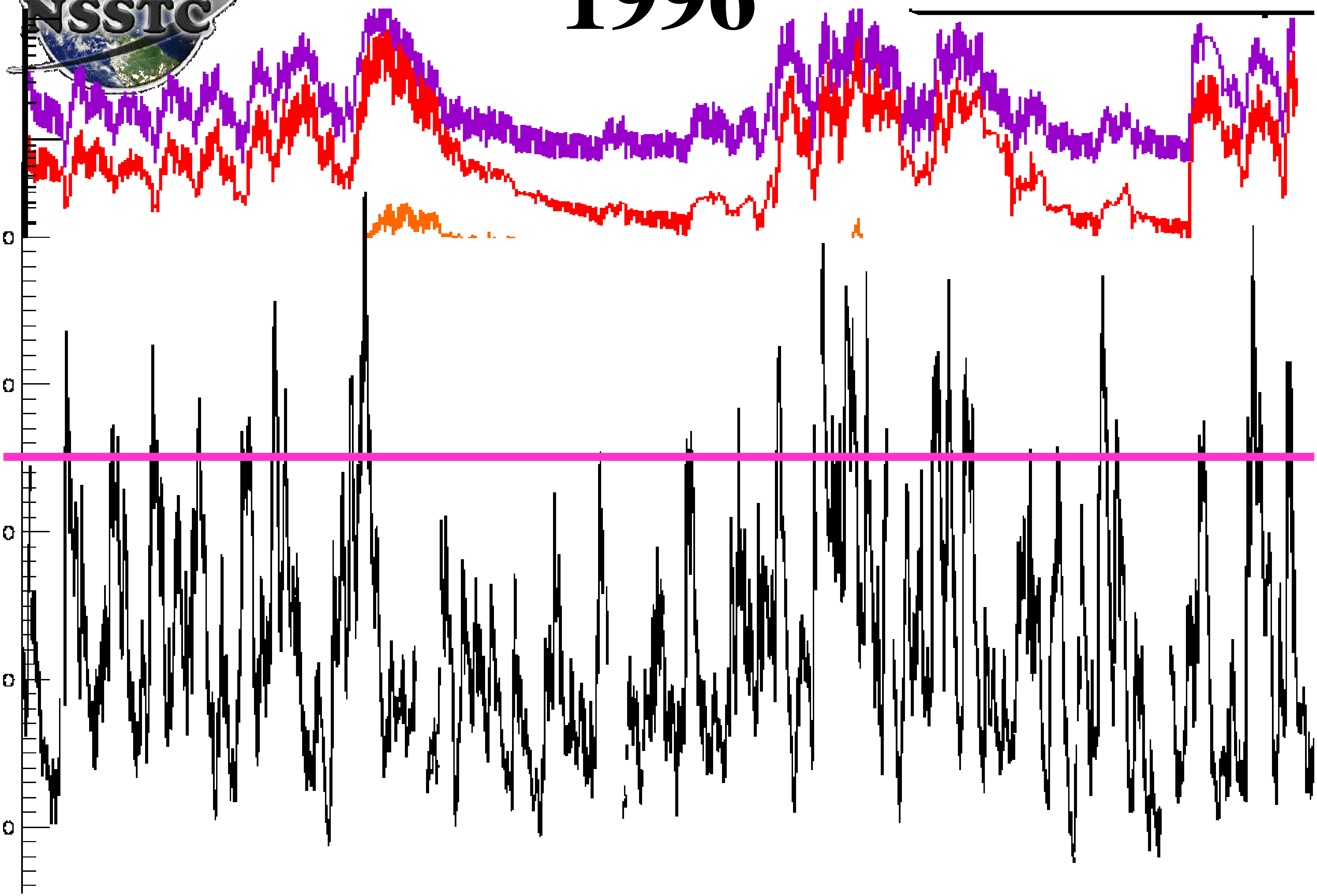


Yohkoh SXT, Dec 10, 1995 -Apr 15, 1996

1996

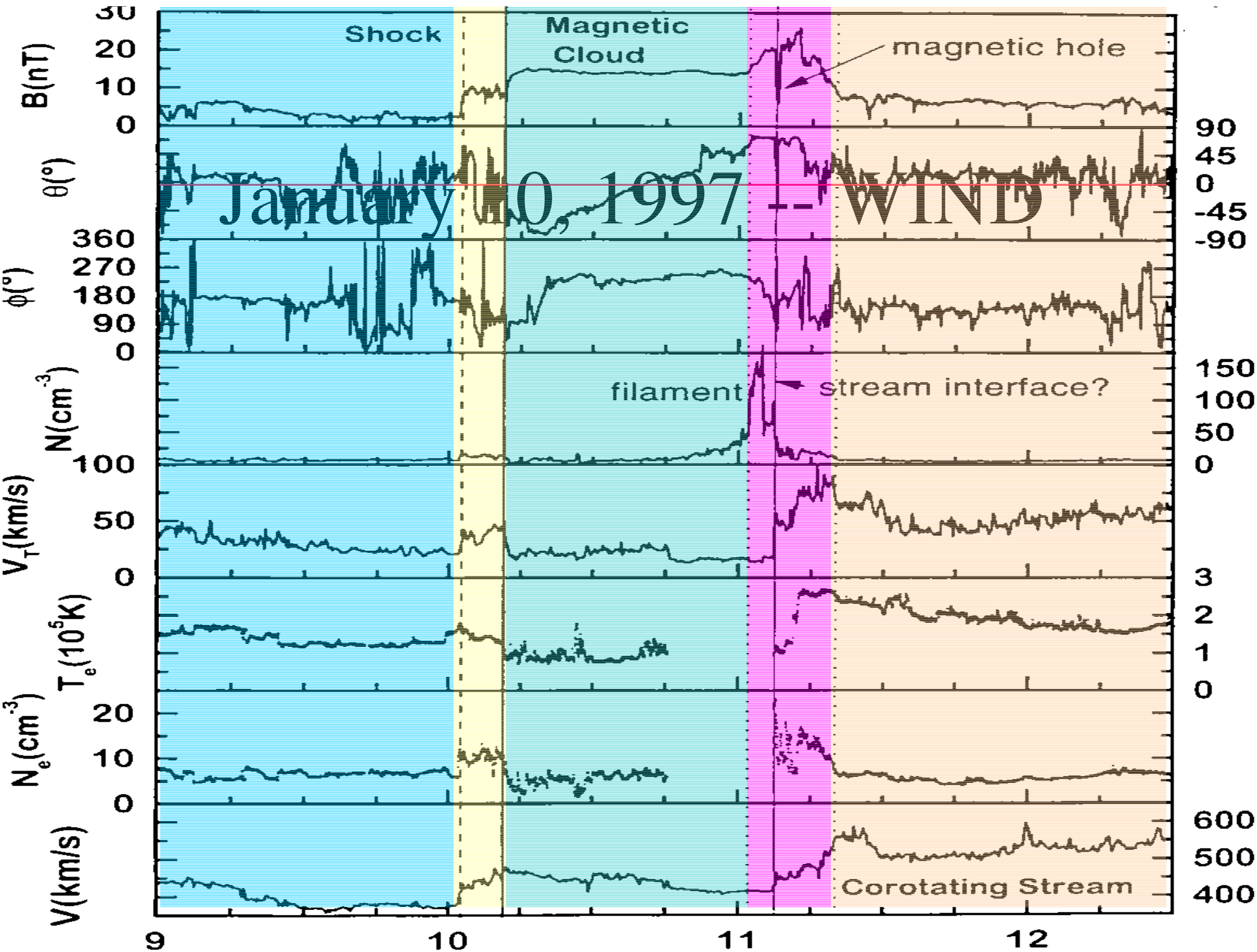


1996



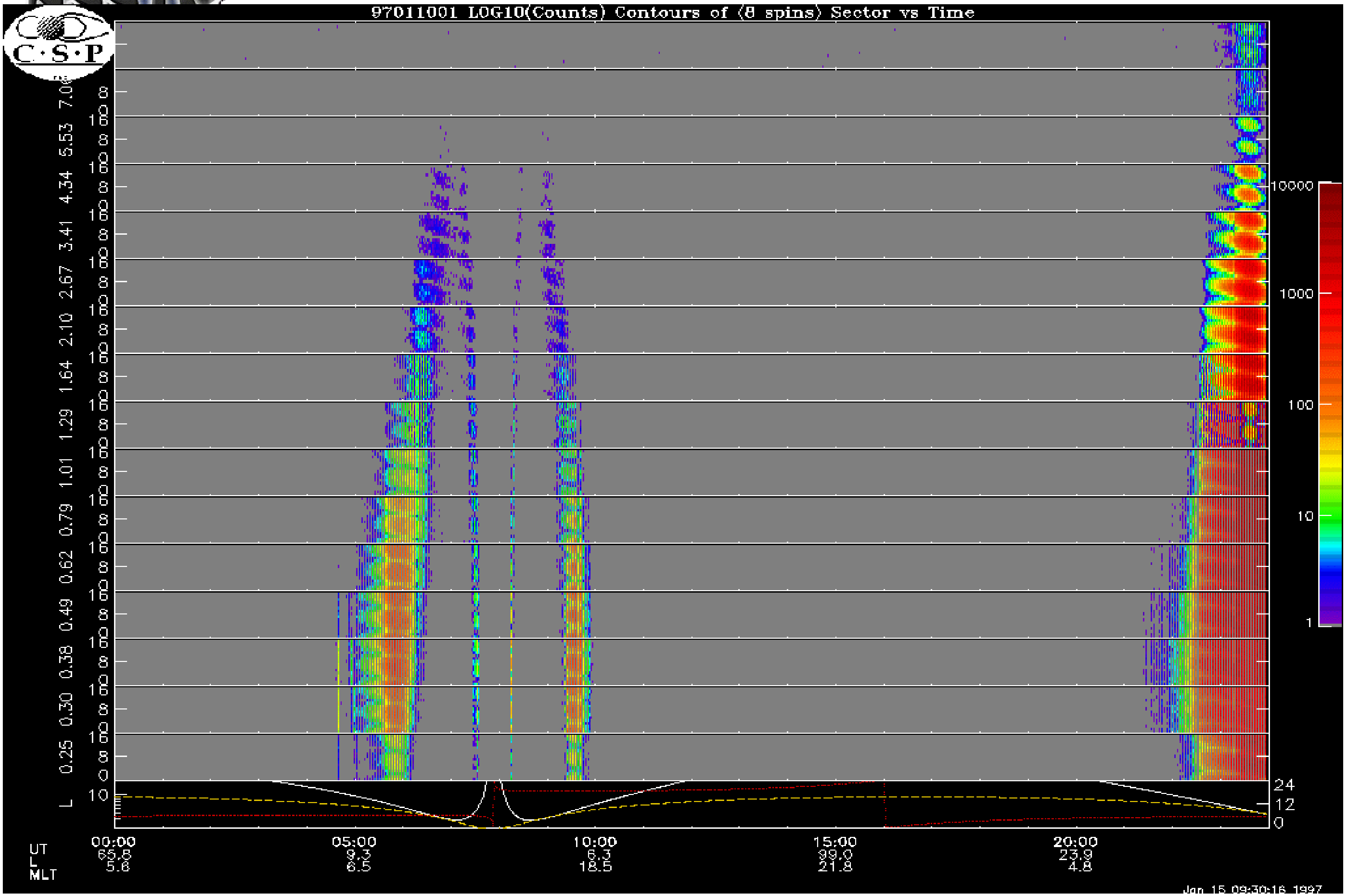
Jan 10-11, 1997

Telstar 401 dies, costs AT&T $12M
after insurance.

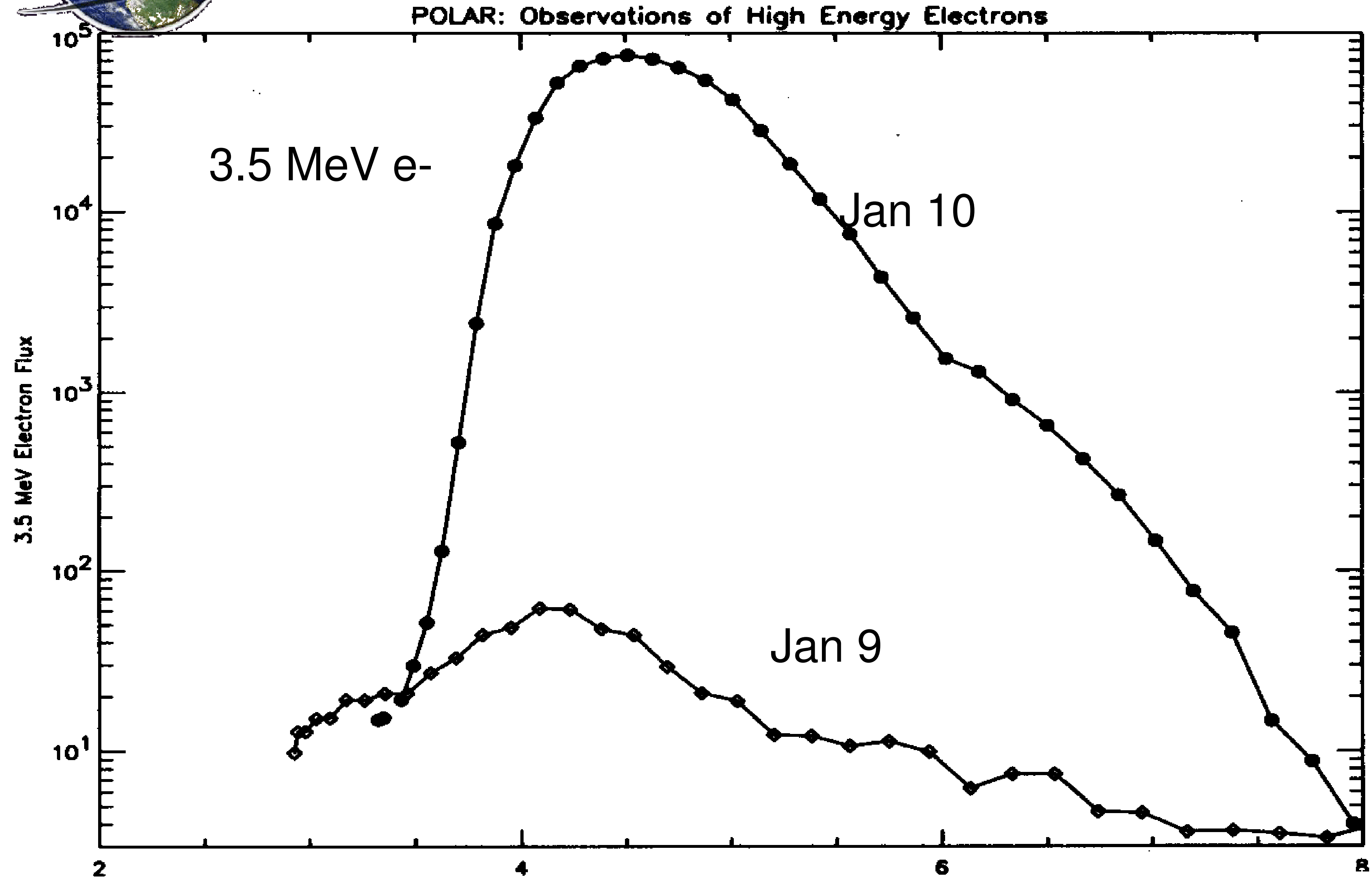


January 10, 1997 -- WIND
Shock
Magnetic Cloud
magnetic hole
filament
stream interface?
Corotating Stream
B(nT)
θ(°)
φ(°)
N(cm^-3)
V_T(km/s)
T_e(10^5K)
N_e(cm^-3)
V(km/s)
30
20
10
0
90
45
0
-45
-90
360
270
180
90
0
150
100
50
0
100
50
0
3
2
1
0
20
10
0
600
500
400
9
10
11
12

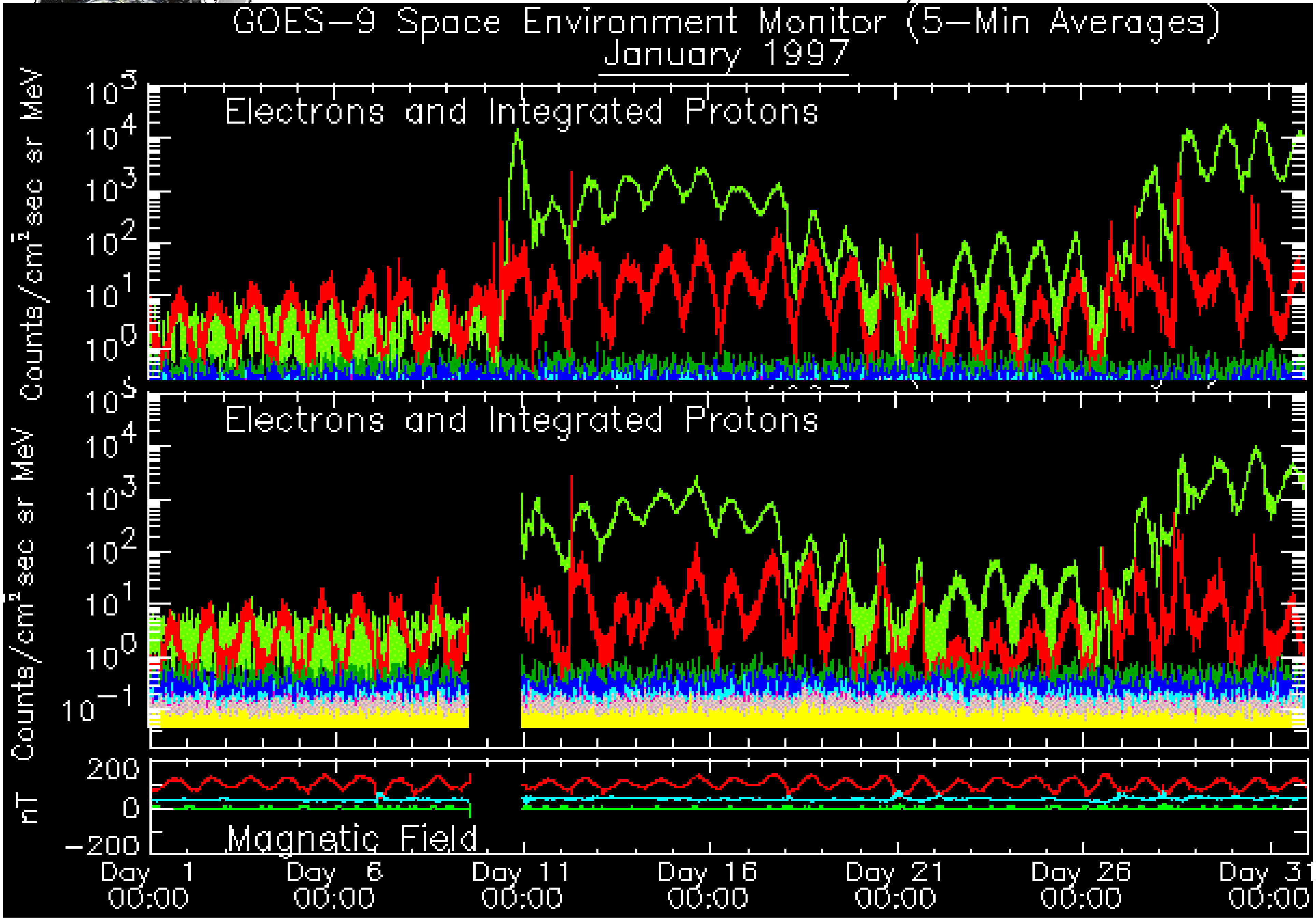
JAN 10, 1997 (HIST 300-7000 keV e-)



POLAR/HIST 3.5 MeV Electrons



E>3 MeV Electrons, GOES 8+9



Empirical Prediction (trying to predict the DOW)

- McIlwain 1966: Geo MeV e increases
- Paulikas & Blake 1979: Vsw best external predictor
- Nagai 1988: Kp best internal predictor
- Baker 90 LPF, Koons&Gorney 90 NN
- Li & 03: Ext BC+internal diffusion→ predictor
- Dmitriev03 Log-Lin,Ukhorskiy04 NonLinear, Ballatore 04 breakpoint at V=550km/s
- Problem: they don't work on the big extreme events (Koons 04). Why? More physics needed.

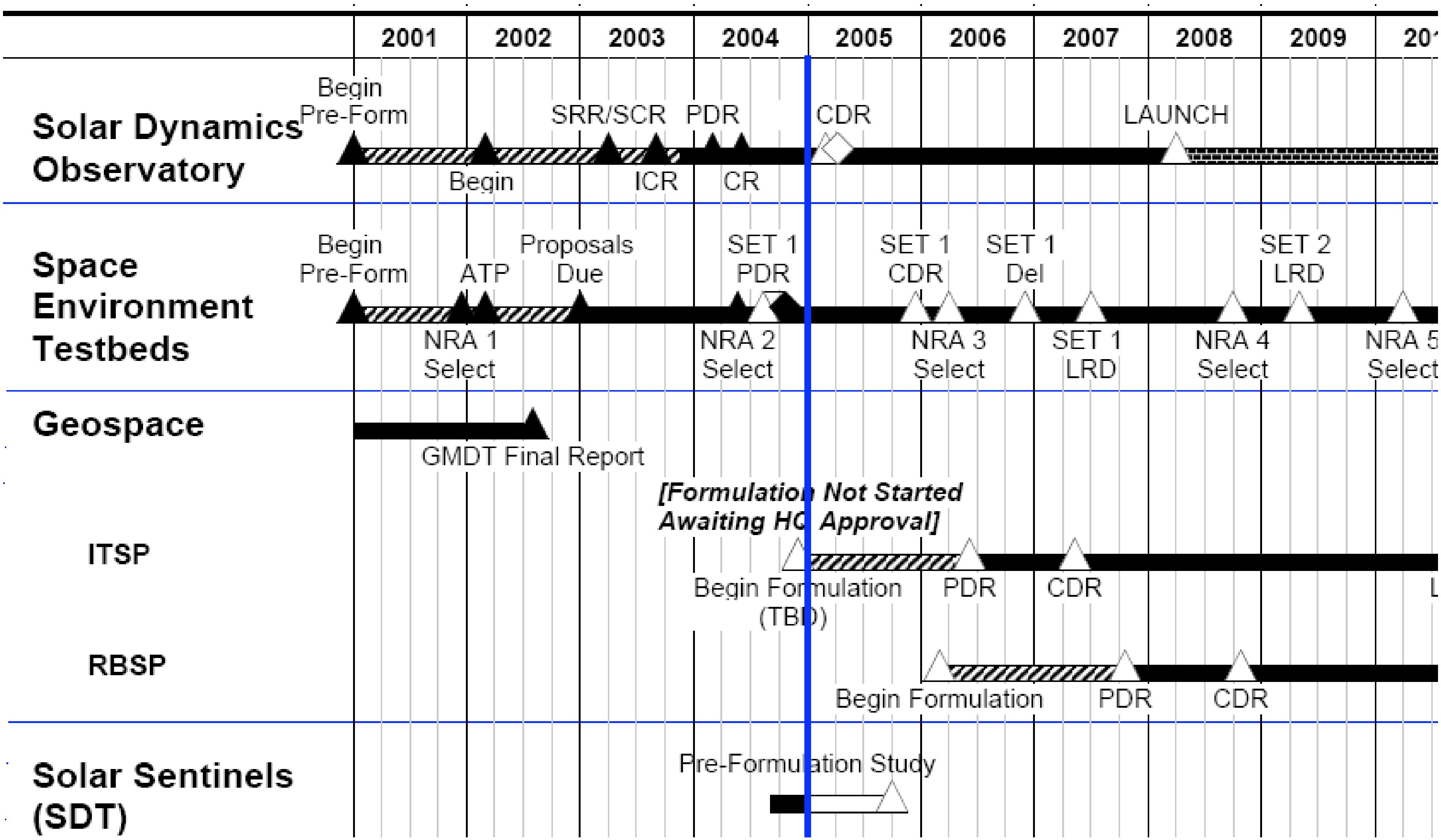
Sun-Earth Transducers

- Proton pressure → Bow shock, hot plasma (100eV electron, 1 kev/nuc ion), thermalized ram energy "Frictional" or "viscous" ($\rho V^{5/2}$)
- Impulsive → SSC, shock acceleration, Fermi, radial diffusion, Kp, "mechanical" (ρV^2)
- Fields → Polar cap potential, convection, ring current, Dst, AE, "electrical" (V*Bz) [ICME]
- What transducer is Sun→ ORBE? Vsw! Poor correlation with all of the above (they add noise)!

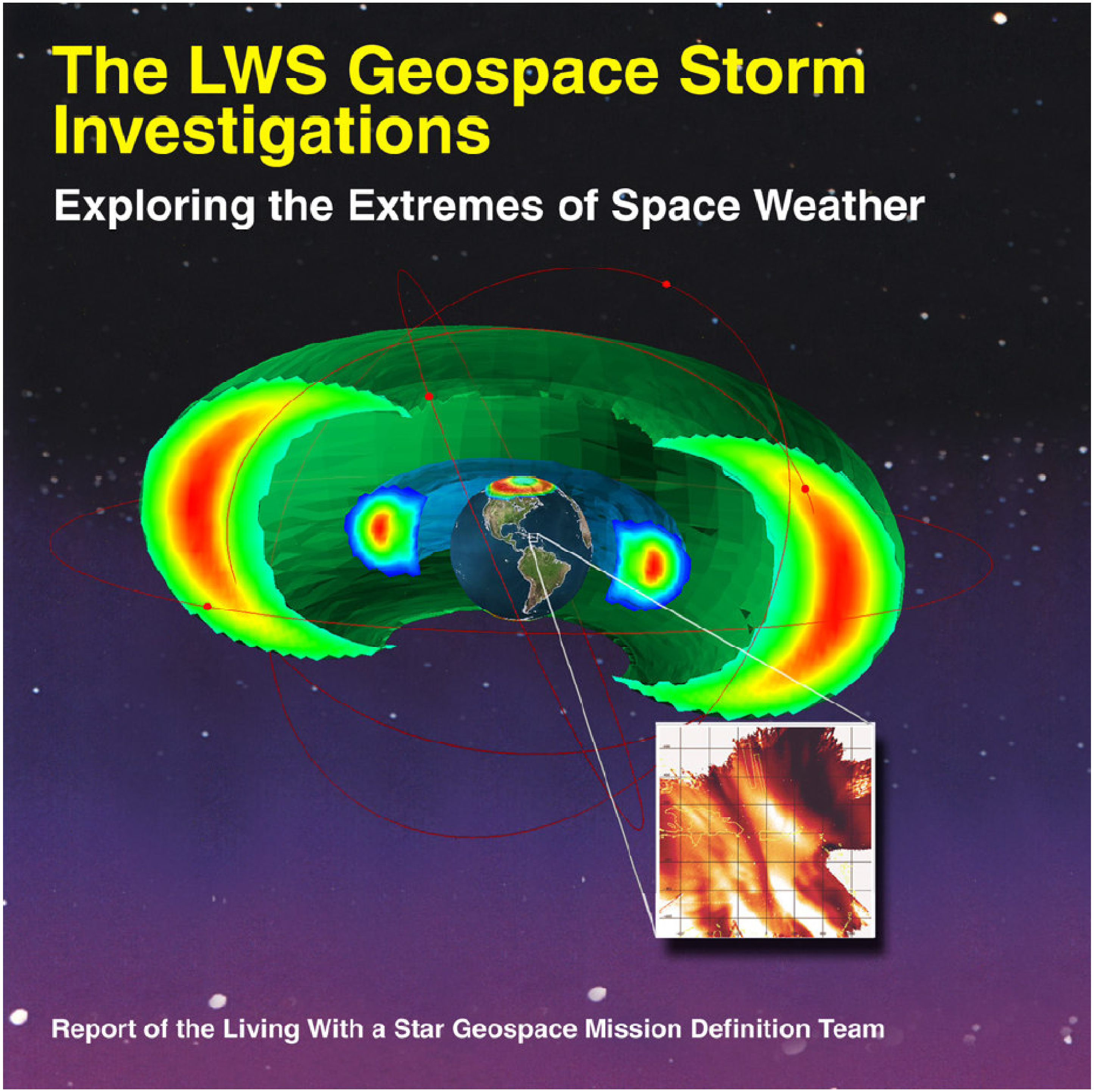
Living With A Star

RBSP Mission Objectives

LWS plan


2001
2002
2003
2004
2005
2006
2007
2008
2009
201
Solar Dynamics Observatory
Begin Pre-Form
SRR/SCR
PDR
CDR
LAUNCH
Begin
ICR
CR
Space Environment Testbeds
Begin Pre-Form
ATP
Proposals Due
SET 1 PDR
SET 1 CDR
SET 1 Del
SET 2 LRD
NRA 1 Select
NRA 2 Select
NRA 3 Select
SET 1 LRD
NRA 4 Select
NRA 5 Select
Geospace
GMDT Final Report
[Formulation Not Started Awaiting HQ Approval]
ITSP
Begin Formulation (TBD)
PDR
CDR
RBSP
Begin Formulation
PDR
CDR
Solar Sentinels (SDT)
Pre-Formulation Study

Sept., 2002 GMDT Report



GMDT conclusions

LWS/Geospace General Objective:	Specific Objectives:
Priority 1: Understand the acceleration, global distribution, and variability of energetic electrons and ions in the inner magnetosphere. SAT report: WG1-5 and 6, WG2-4	**Priority 1:** **1.1**: Differentiate among competing processes affecting the acceleration and transport of outer radiation belt electrons.
	Priority 2: **1.2a**: Differentiate among competing processes affecting precipitation and loss of outer radiation belt electrons. **1.2b**: Understand the creation and decay of new electron radiation belts. **1.2c**: Develop and validate physics-based data assimilation and specification models of outer radiation belt electrons.
	Priority 3: **1.3a**: Understand the role of "seed" or source populations for relativistic electron events. **1.3b**: Quantify the relative contribution of adiabatic and nonadiabatic processes on energetic electrons. **1.3c**: Understand the effects of the ring current and other storm phenomena on radiation belt electrons and ions.
	Priority 4: **1.4a**: Understand how and why the ring current and associated phenomena vary during storms. **1.4b**: Develop and validate physics-based and specification models of inner belt protons for solar cycle time scales.
Priority 2A: Determine the effects of long- and short-term variability of the Sun on the global-scale behavior of the ionospheric electron density. SAT report: WG1-1, WG2-1	**Priority 1:** **2A.1a**: Quantify the relationship between the magnitude and variability of the solar spectral irradiance and the global electron density. **2A.1b**: Quantify the effects of geomagnetic storms on the electron density.
	Priority 2: **2A.2**: Quantify how the interaction between the neutral atmosphere and the ionosphere affects the distribution of ionospheric plasma.
	Priority 3: **2A.3**: Discover the origin and nature of propagating disturbances in the ionosphere.
Priority 2B: Determine the solar and geospace causes of small-scale ionospheric density irregularities in the 100 to 1000 km altitude range. SAT report: WG1-2, WG2-2	**Priority 1:** **2B.1**: Characterize and understand the origin and evolution of newly-discovered storm-time mid-latitude ionospheric irregularities.
	Priority 2: **2B.2a**: Understand the conditions leading to the formation of equatorial spread-F irregularities, and their location, magnitude and spatial and temporal evolution. **2B.2b**: Understand the conditions leading to the formation of polar patches and their high-latitude irregularities.
	Priority 3: **2B.3**: Enable prediction of the onset, location, and development of E-region irregularities.
Priority 3A: Determine the effects of solar and geospace variability on the atmosphere enabling an improved specification of the neutral density in the thermosphere. SAT report: WG1-3, WG2-3	**Priority 1:** **3A.1a**: Determine the variability in the neutral atmosphere attributable to the solar EUV spectral irradiance. **3A.1b**: Determine the variability in the neutral atmosphere attributable to magnetospheric inputs.
	Priority 2: **3A.2**: Determine the variability in the neutral atmosphere attributable to internal processes.
	Priority 3: **3A.3**: Determine the variability in the neutral atmosphere attributable to atmospheric waves from below.

Priority 1:

1.1: Differentiate among competing processes affecting the acceleration and

Priority 2:

1.2a: Differentiate among competing processes affecting precipitation and loss of outer radiation belt electrons.

1.2b: Understand the creation and decay of new electron radiation belts.

1.2c: Develop and validate physics-based data assimilation and specification models of outer radiation belt electrons.

Priority 3:

1.3a: Understand the role of "seed" or source populations for relativistic electron events.

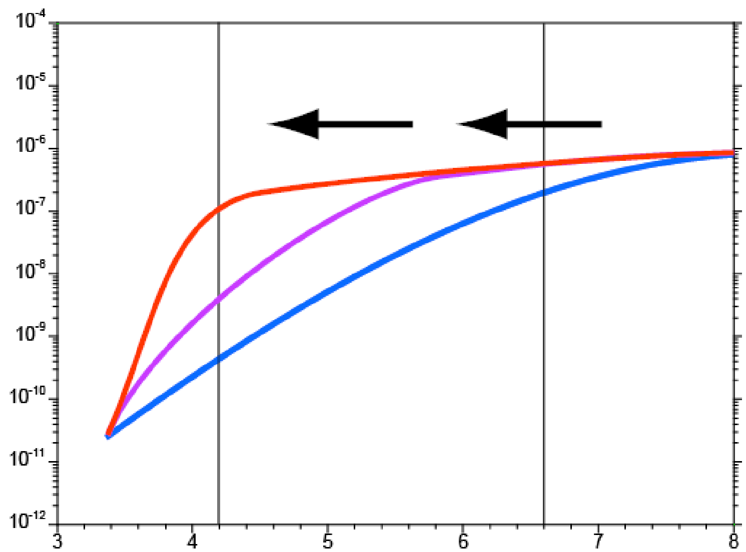
1.3b: Quantify the relative contribution of adiabatic and nonadiabatic processes on energetic electrons.

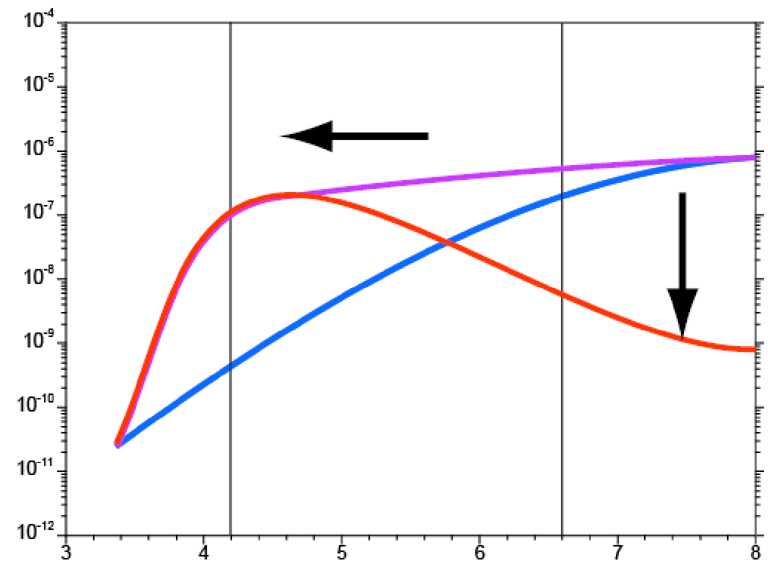
1.3c: Understand the effects of the ring current and other storm phenomena on radiation belt electrons and ions.

GMDT Mission Description

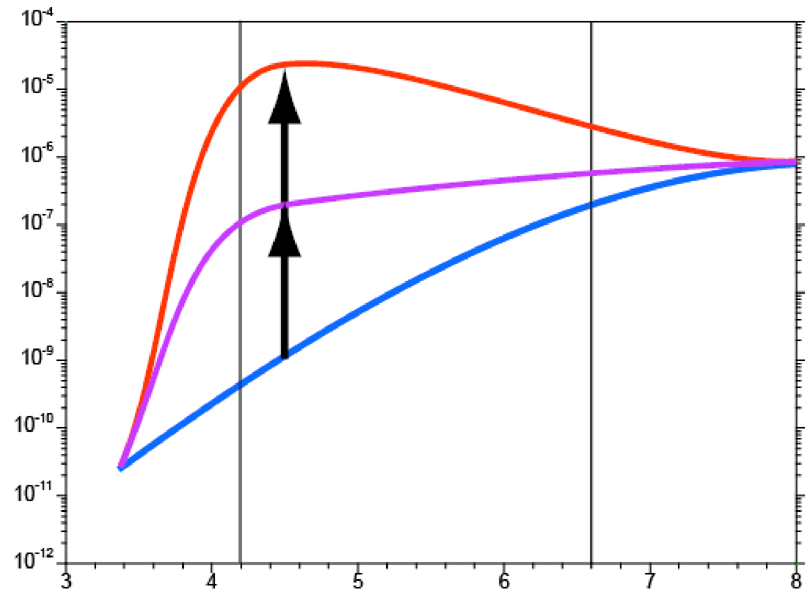
Parameter	Value	Driver
Mission life	2 yr, 5 yr expendables	Radiation shielding
Orbit	500 $\times$ 30,600 cm <18° inc., 12° goal “chasing” orbits	Magnetic L-shell coverage Particle distribution measurements
Orientation	Spinner Spin axis <15° from Sun Spin rate about 5 rpm	Simplify solar array design *E*-field measurements need even lighting on two sensors
Attitude knowledge	1°, 0.3° goal, 3σ	Flux gate magnetometer Search coil magnetometer
Attitude control	2°, 3σ	Spin axis <15° from Sun
Cleanliness	Magnetically clean Electromagnetically clean	Magnetometers Search coil magnetometer

ORBITALS 2004 Conference





1) Diffusion from outside
2) Diffusion & Loss
3) Internal acceleration



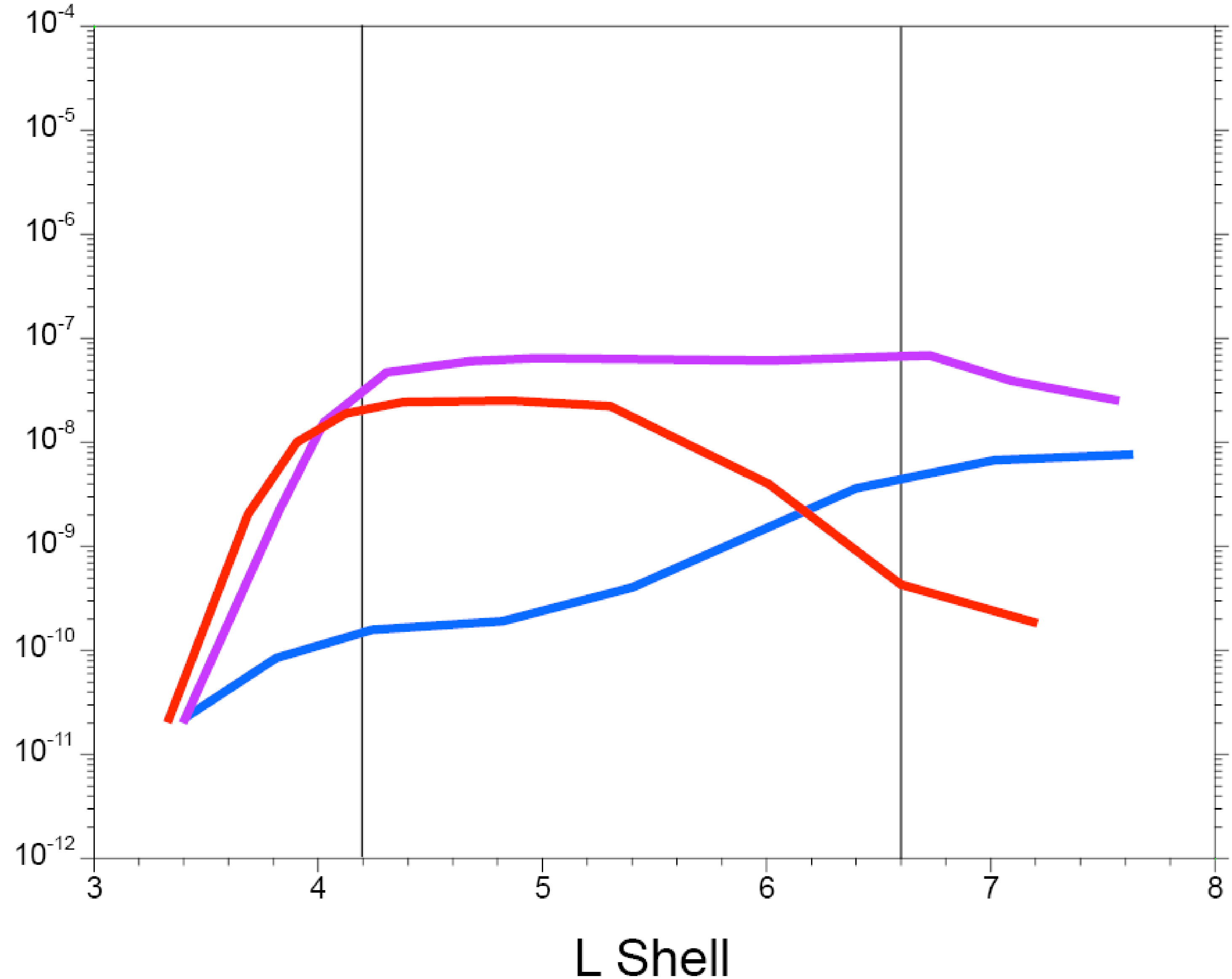
Selesnick & Blake Summary

μ = 600 MeV/G

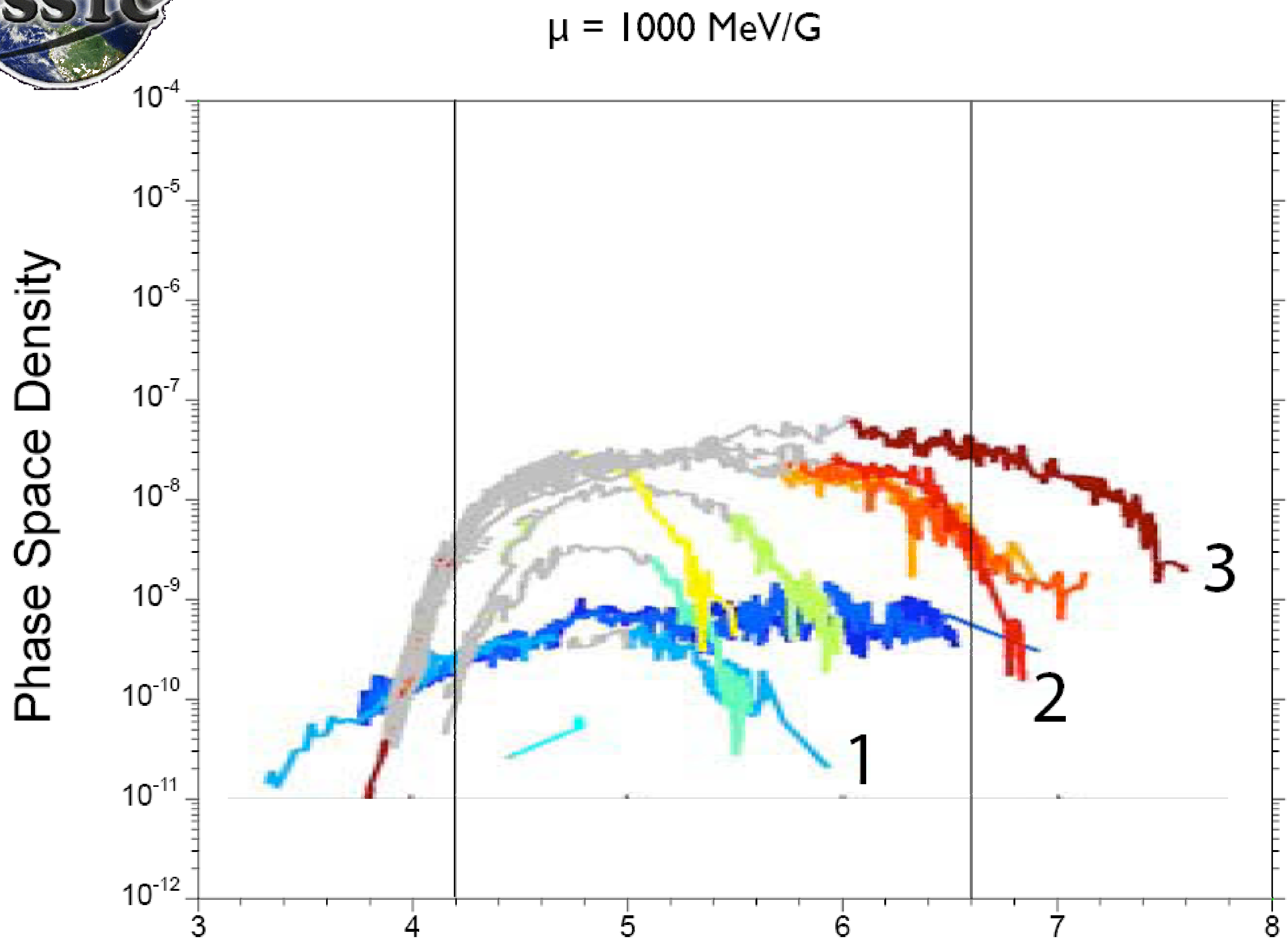
BEFORE

DURING

AFTER

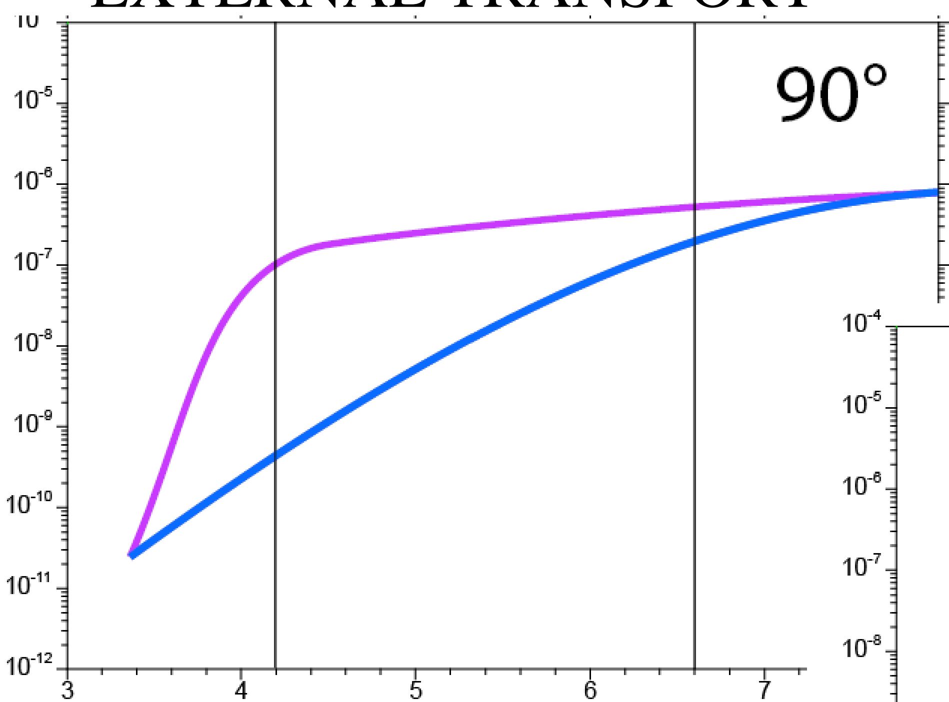


Green & Kivelson Summary

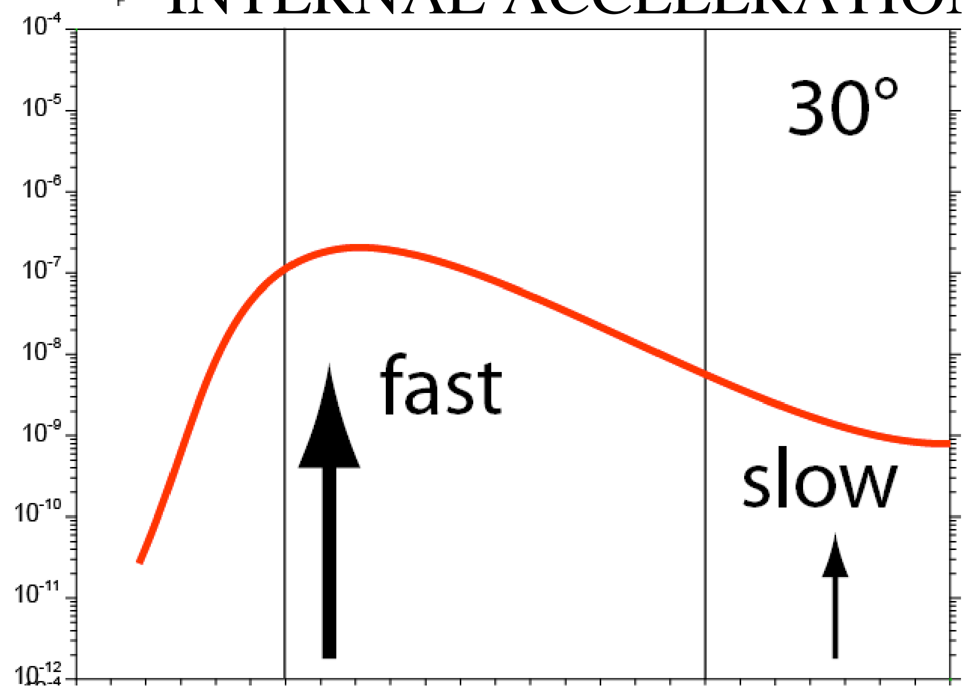


Expected Pitchangle Variations

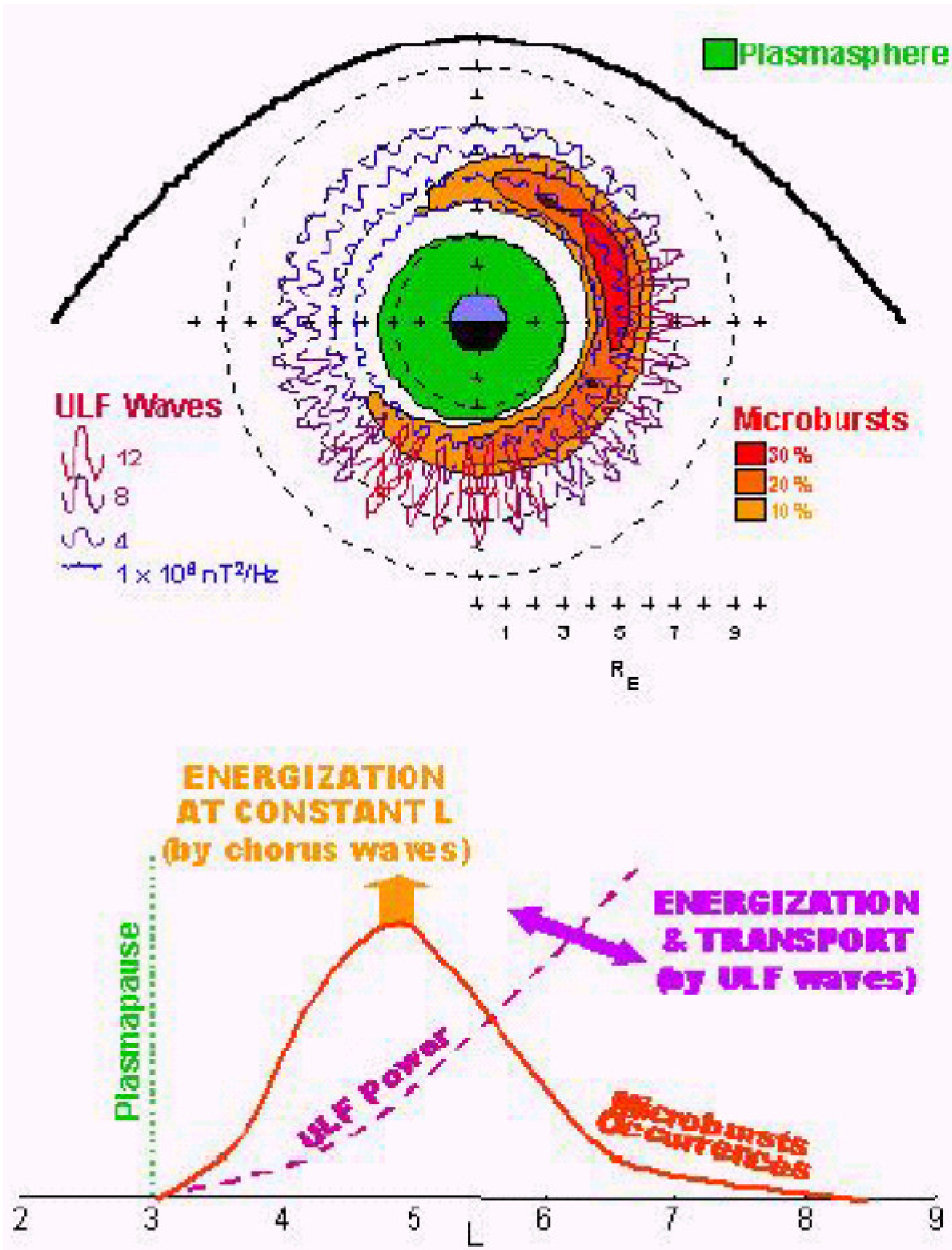
EXTERNAL TRANSPORT



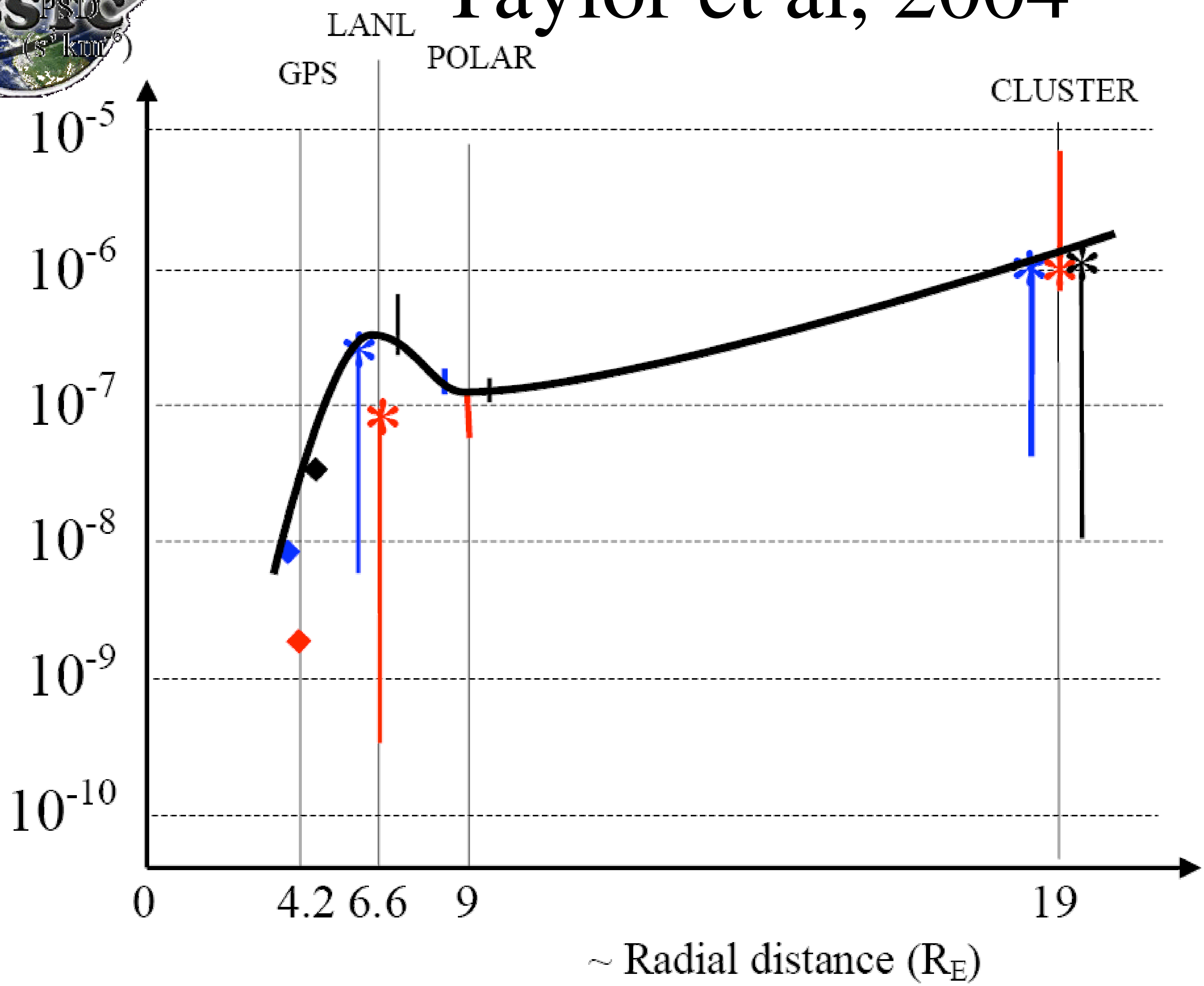
INTERNAL ACCELERATION



The VLF→ULF Theory of MeV electron production



Taylor et al, 2004



What's Needed (Reeves04)

- Near-equatorial Phase Space Density
  - measurements
  - pitch angle resolved particle fluxes
  - local magnetic field measurements
  - global magnetic field model
- Multi-point measurements with
  - simultaneous measurements at different ΔL
  - simultaneous measurements at different ΔMLT
- Ancillary measurements of particles and fields

A Brief Introduction to Cusp MeV electron theory

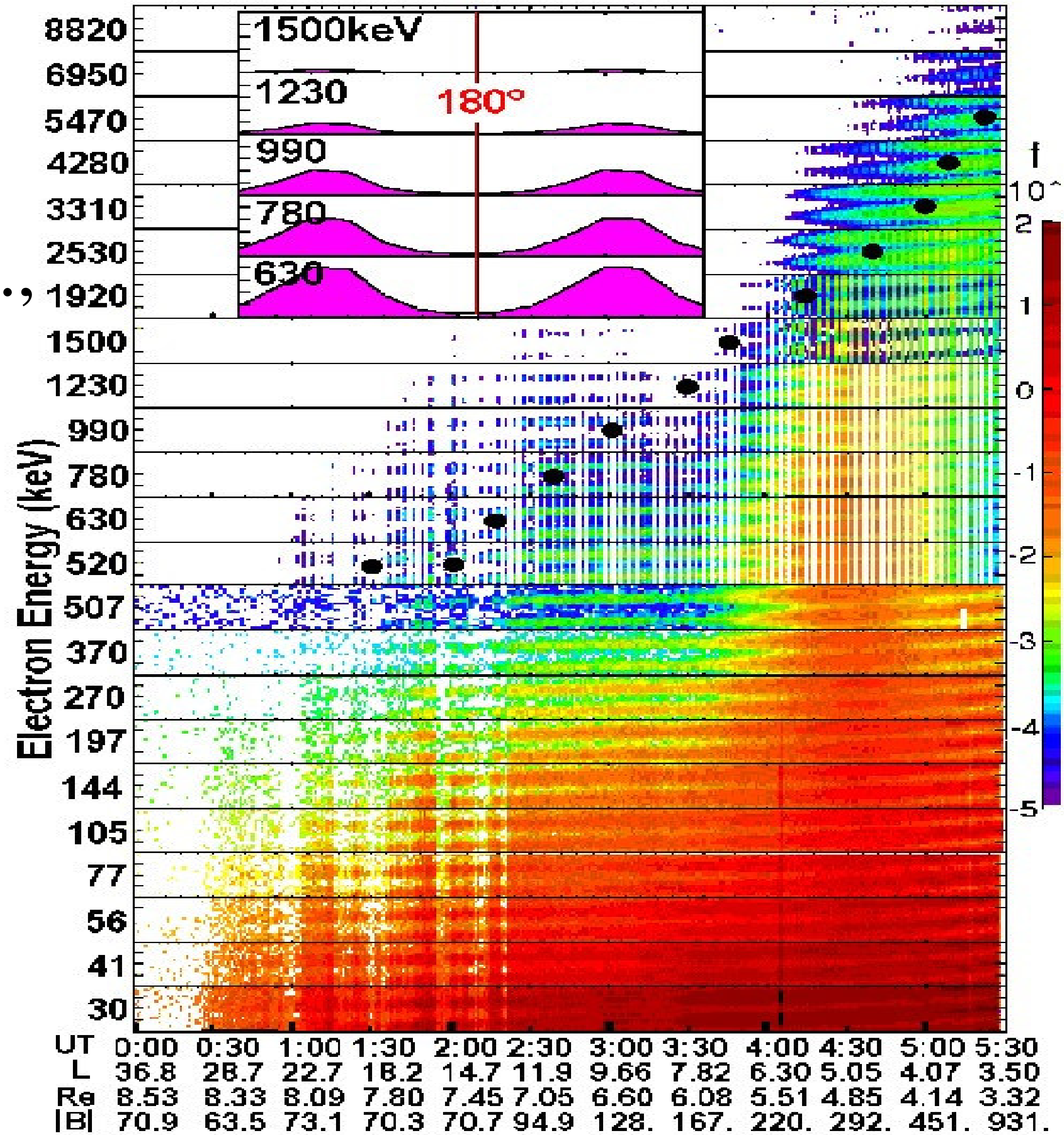
The next 12 slides were skipped in the original talk.

Sheldon et al., GRL 1998

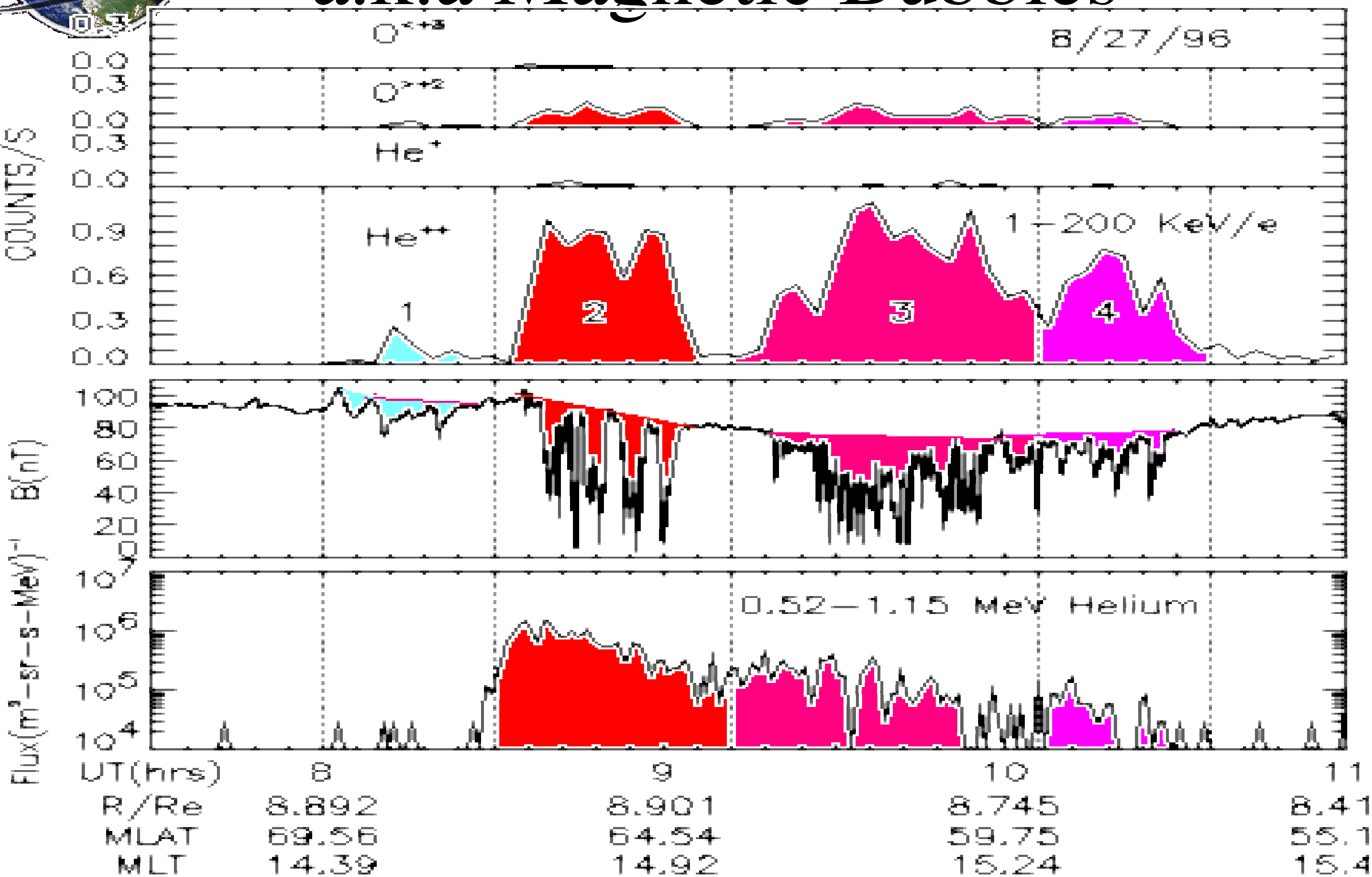
POLAR/ CAMMICE data

1 MeV electron

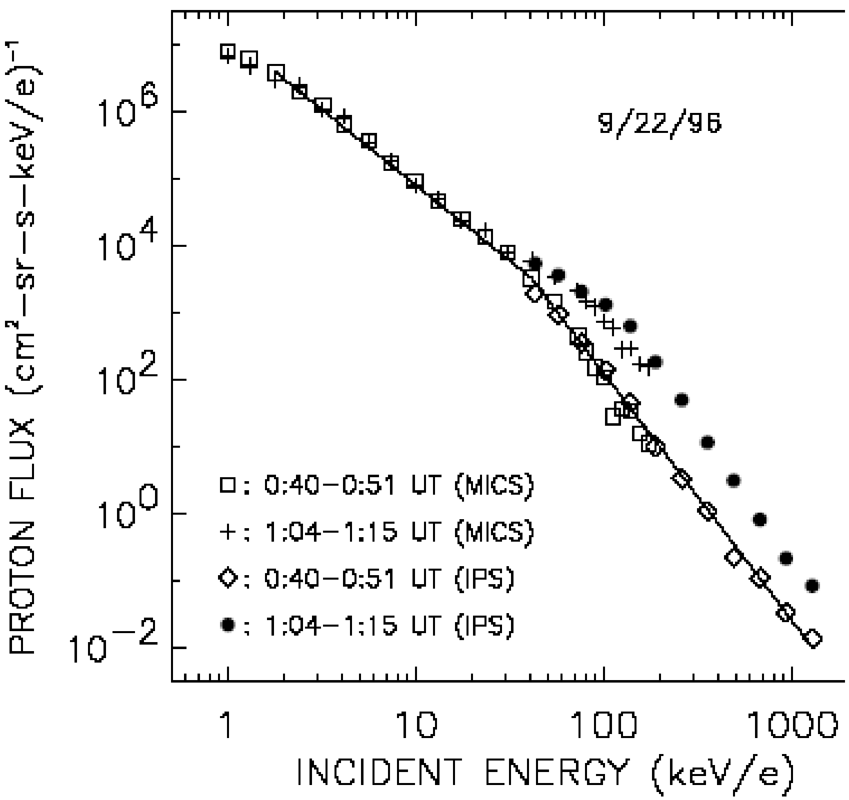
PSD in outer cusp



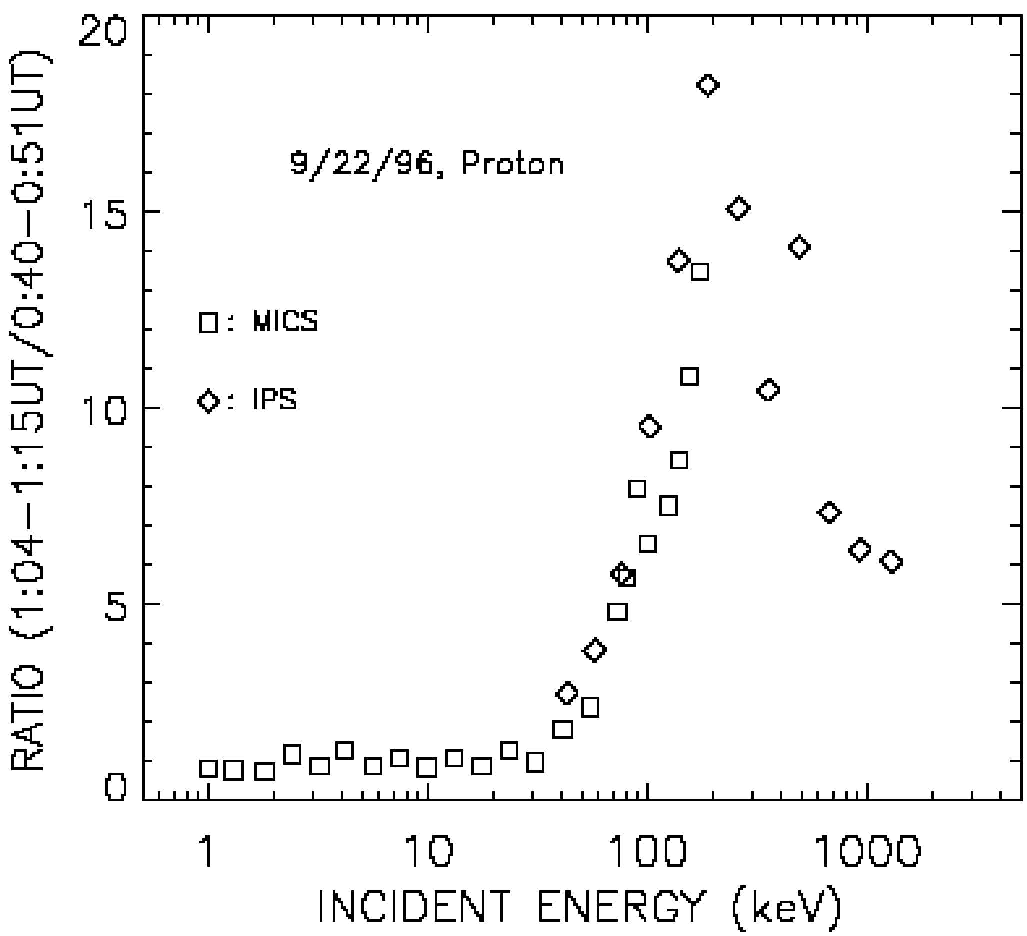
Cusp Diamagnetic Cavities a.k.a Magnetic Bubbles



CEP (Ions)

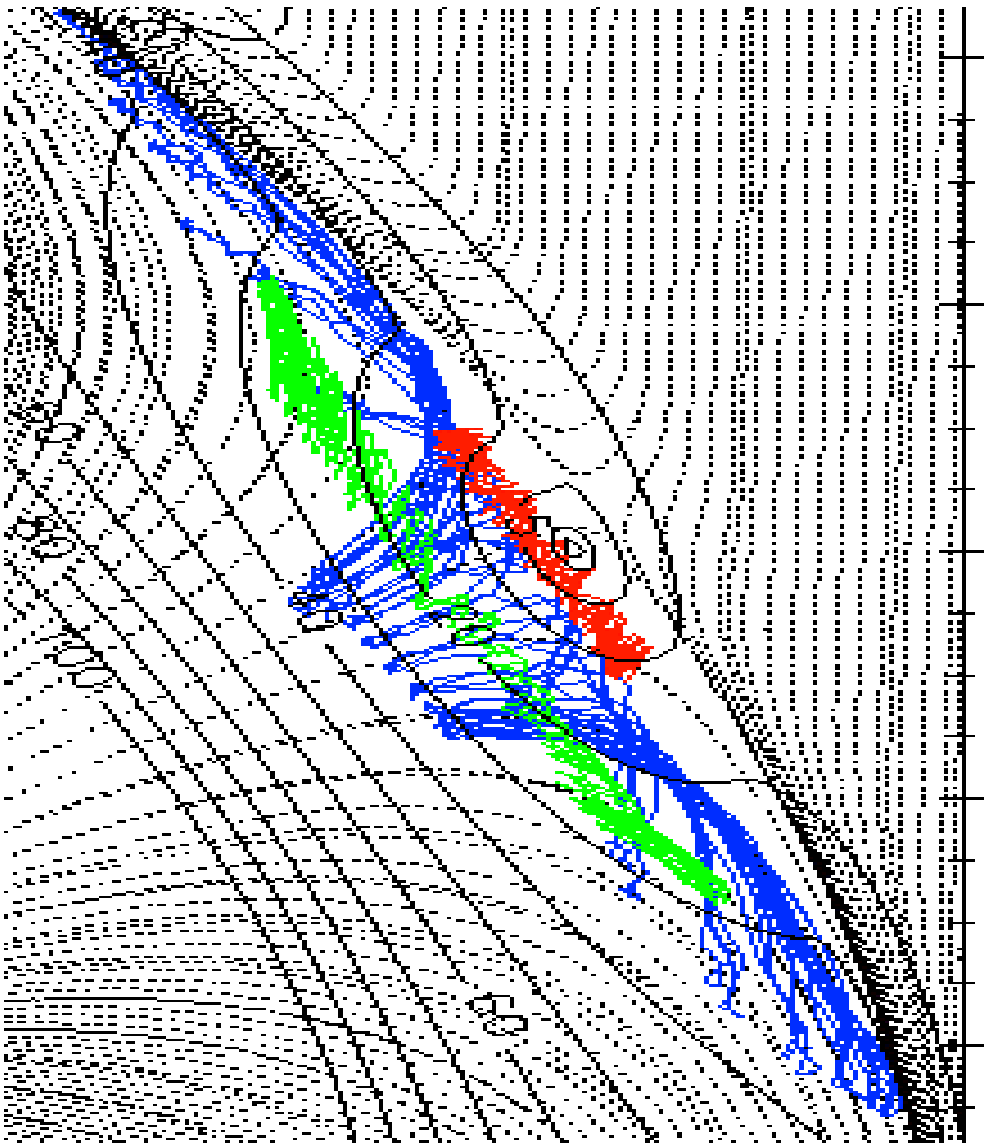


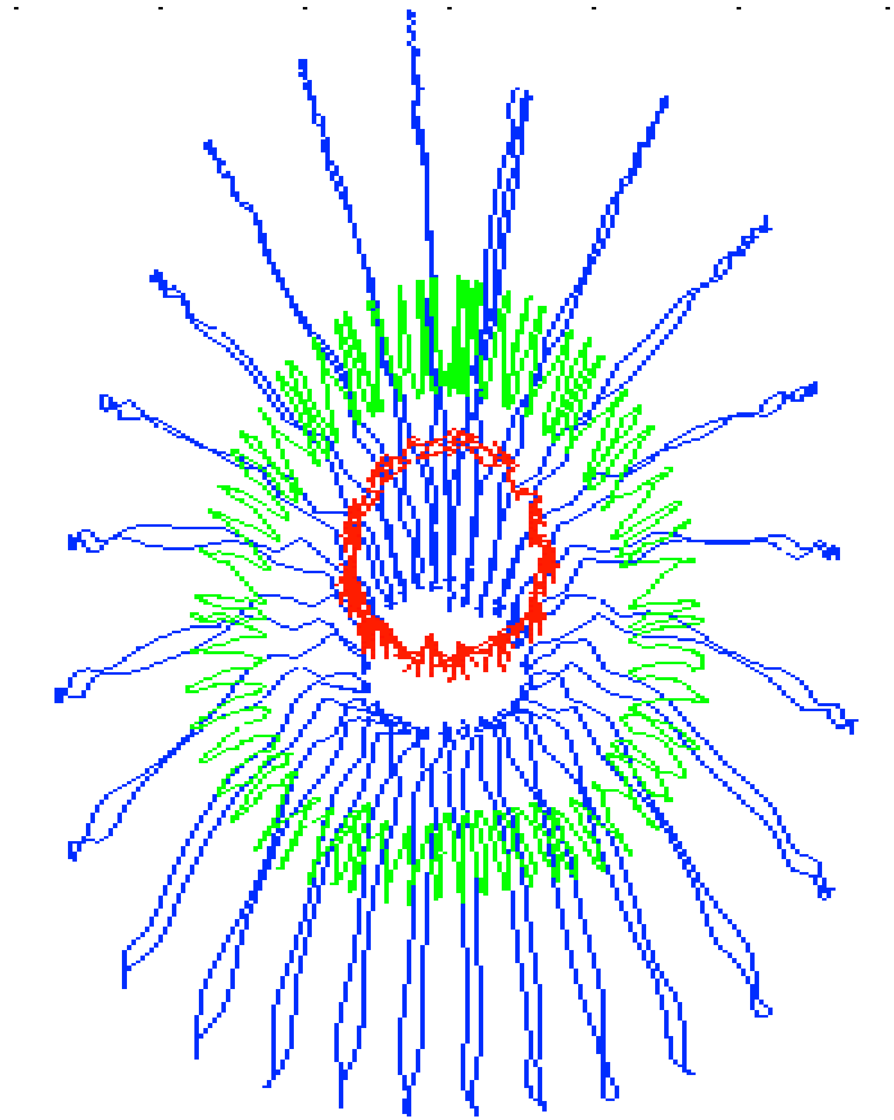
9/22/96
□: 0:40–0:51 UT (MICS)
+: 1:04–1:15 UT (MICS)
◇: 0:40–0:51 UT (IPS)
●: 1:04–1:15 UT (IPS)
PROTON FLUX (cm^2–sr–s–keV/e)$^{-1}$
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
1
10
100
1000
INCIDENT ENERGY (keV/e)

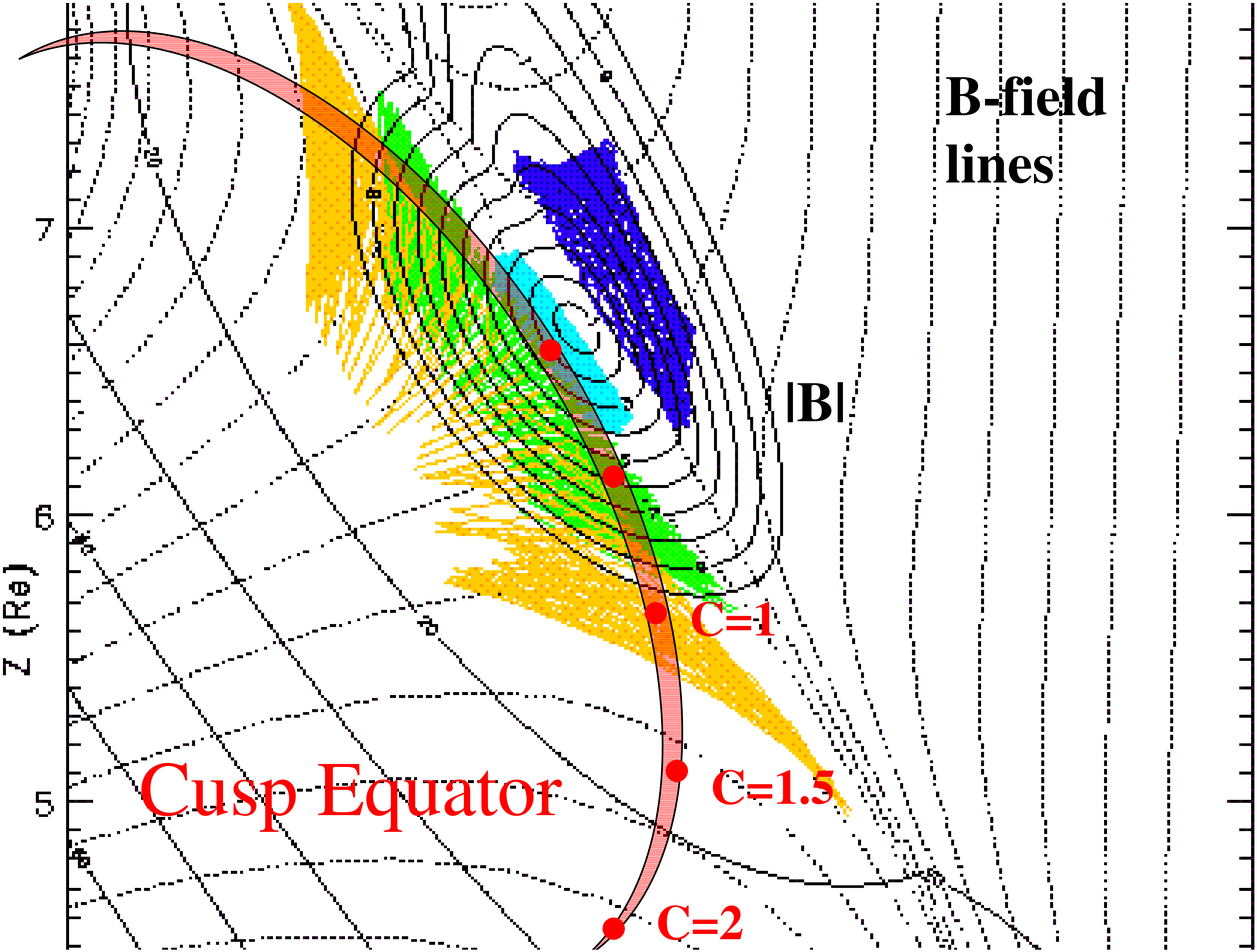


9/22/96, Proton
□: MICS
◇: IPS
RATIO (1:04–1:15UT/0:40–0:51UT)
20
15
10
5
0
1
10
100
1000
INCIDENT ENERGY (keV)

Cusp Theory of External Source





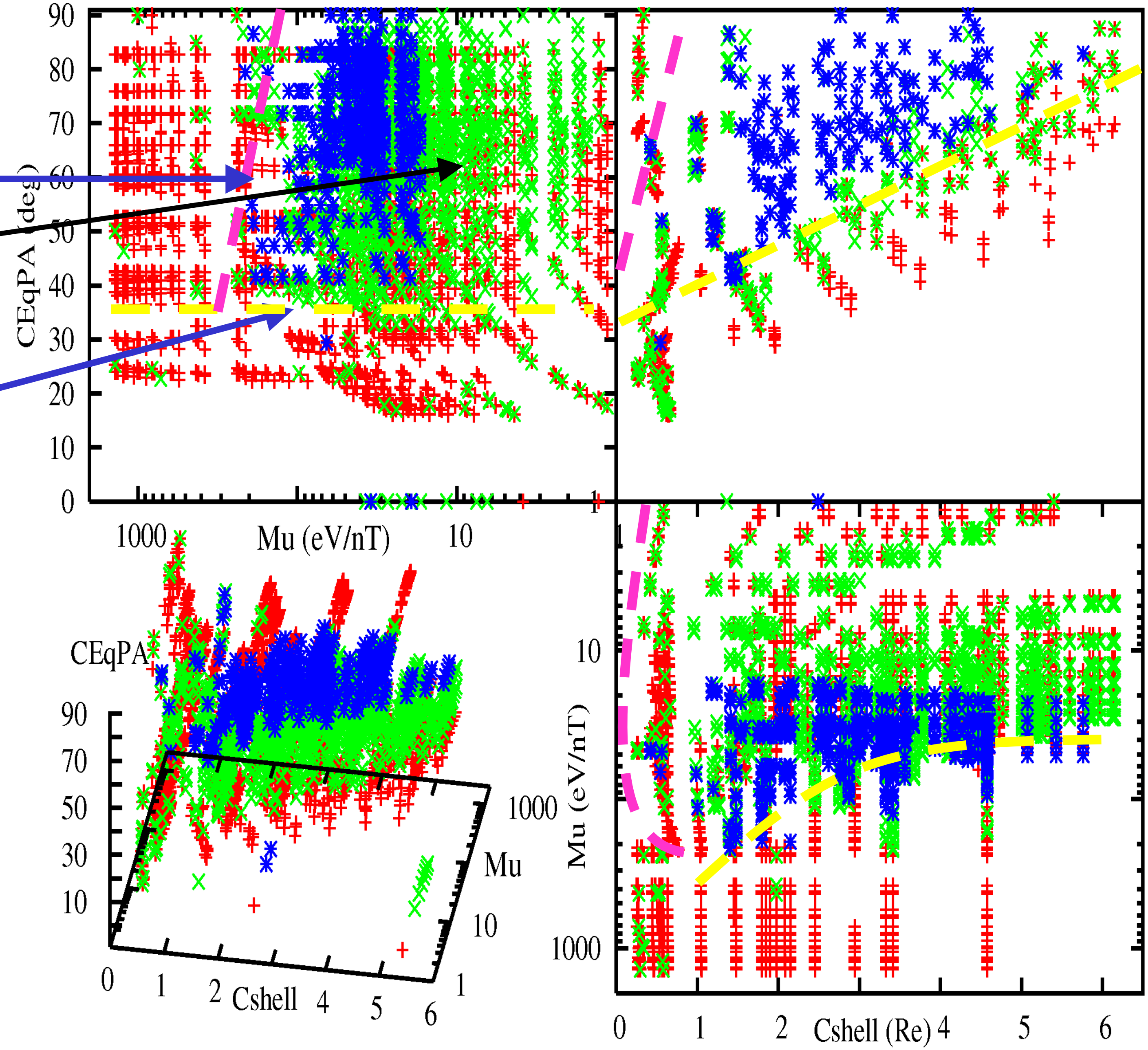

B-field
lines
|B|
C=1
C=1.5
C=2
Cusp Equator
Z (Re)
7
6
5

H^+ Trapping in T96 Cusp

Hi E cutoff

Numerical Roundoff

Loss-cone cutoff



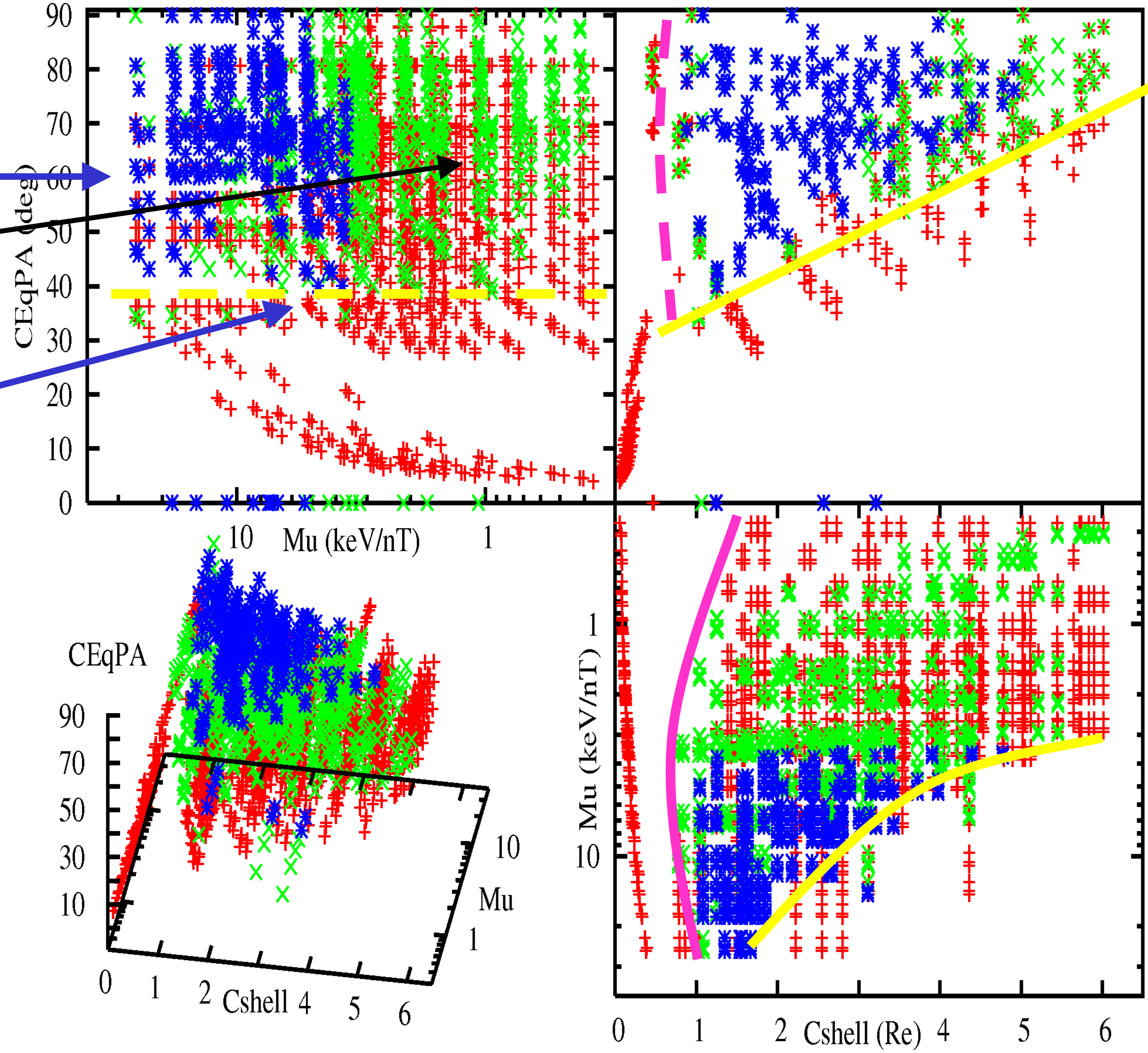
Red= None

Green=Quasi-

Blue= Yes

e^- Trapping in T96 Cusp

Hi E cutoff
Numerical Roundoff
Loss-cone cutoff



Red= None

Green=Quasi-

Blue= Yes

Cusp Provisional Invariant Limits

- Energy Limits (1st invariant at 100nT)
  - Minimum energy, Emin, is defined by cusp “separatrix” energy (ExB = ∇B) ~ 30 keV in the dipole?
  - Max energy, Emax, defined by rigidity.~ 4 MeV e^- (20keV H+)
  - Consequently, no protons are expected to be trapped.
- Pitchangles locally 40-90^o, (2nd invariant)
- Low C-shells are empty below 1 Re for all energy, with a high-Cshell cutoff ~6 inversely dependent on Energy. 1 < C <~6 Re

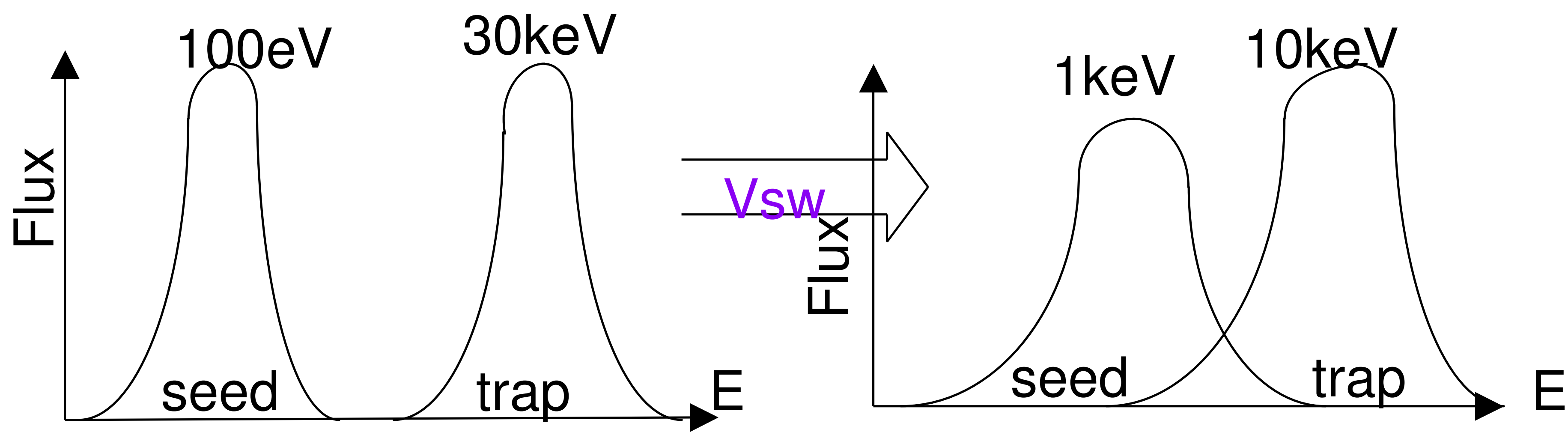
Mapping Cusp to Dipole

- Conserving the 1st invariant, and pitchangle scatter the particles into the cusp-loss cone (<40°), then the particles can appear in the dipole trap, or radiation belts. What would their distribution look like?
  - Energy limits to the rad belts, give ~ 0-100 keV for protons, and 1-15 MeV for electrons.
  - C-shell limits to the dipole give ~5<L<∞?→ very close to the PSD "bump".
  - Mapping pitchangles → 50° < α < 90° at dipole eq?
- Cusp particles look like ORBE injections.

Model

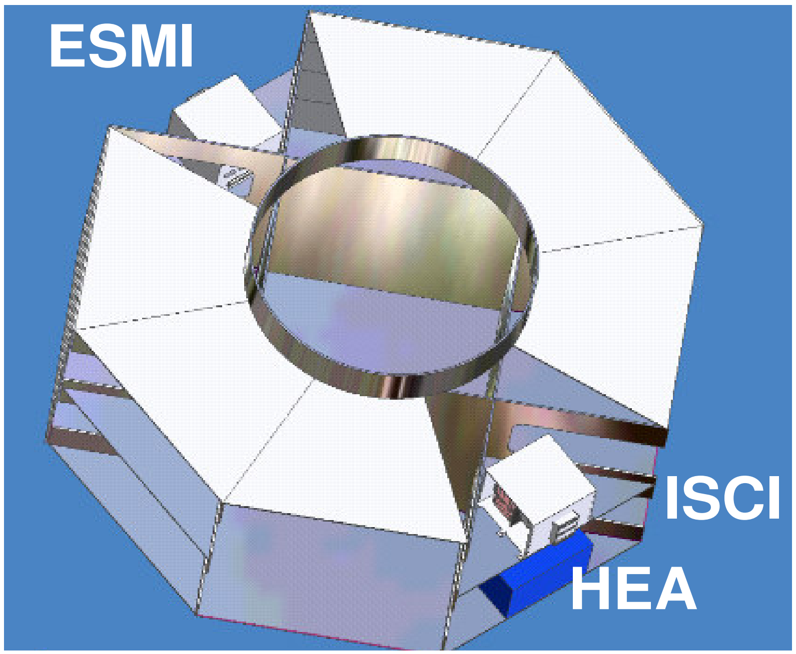
1. Fast solar wind is trapped in the cusp
   – 27 day recurrence, non-linear with Vsw
2. High Alfvenic turbulence of fast SW heats the trap
   – Low Q-value, →compressional, BEN
3. 2^{nd} Order “Fermi” accelerates electrons
   – Low energy appear first, then high w/rigidity cutoff.
4. Trap empties into rad belts simultaneous L=4-10
   – “gentle” evaporation, or “rapid” topology change
   – Initially “butterfly” around 70-deg equatorial

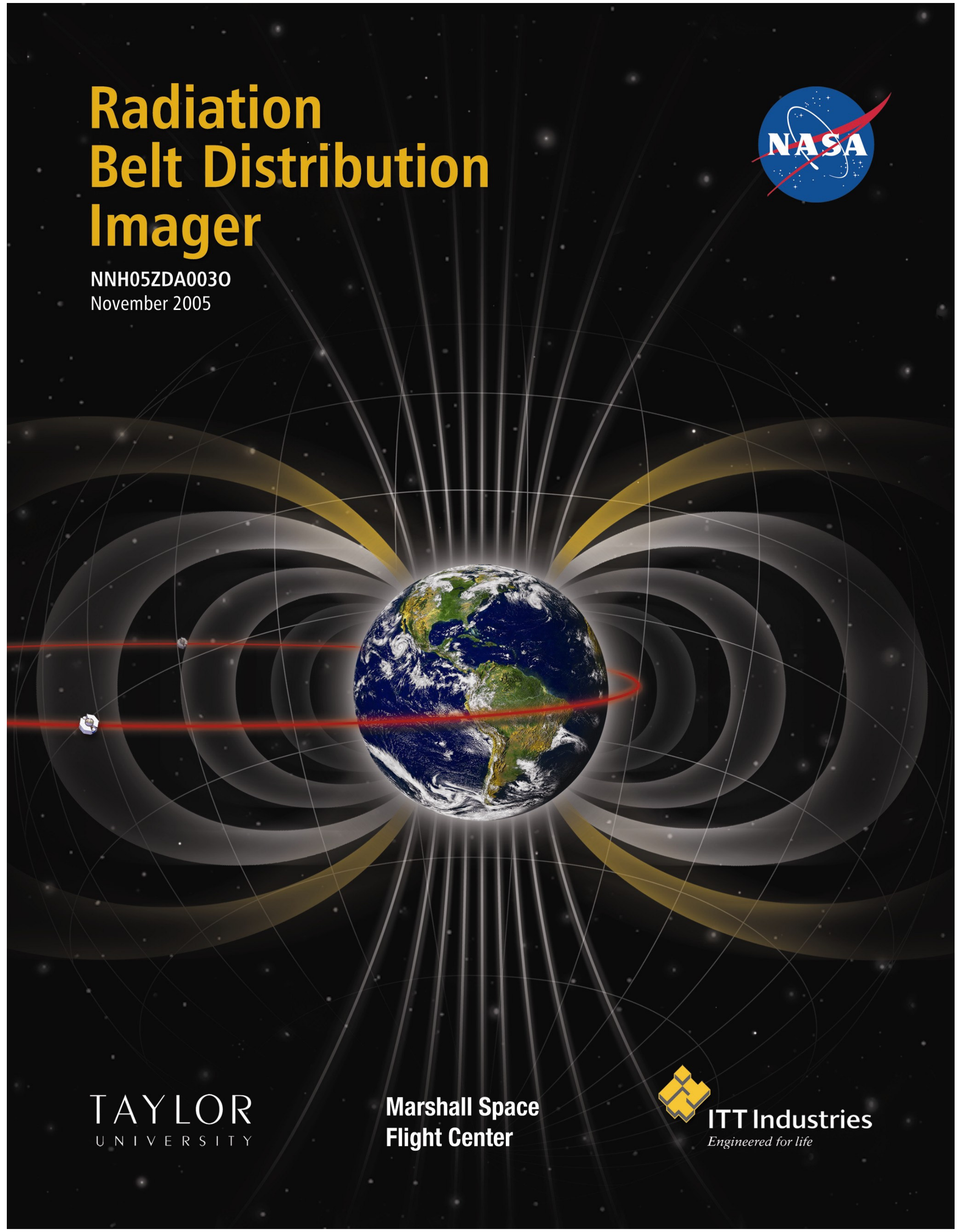
1. Non-Linear Vsw Dependence



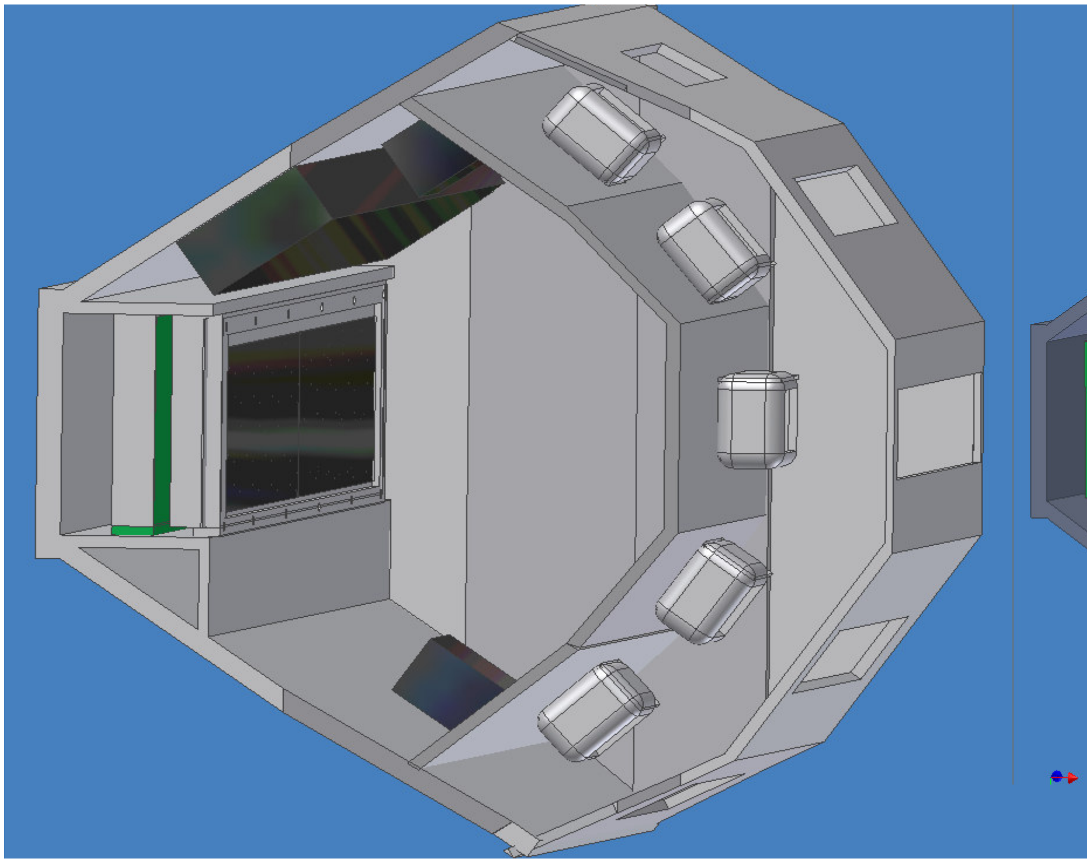
The Reason that Vsw interacts non-linearly is that it does several things at once. It heats the seed population, while also making the trap deeper.

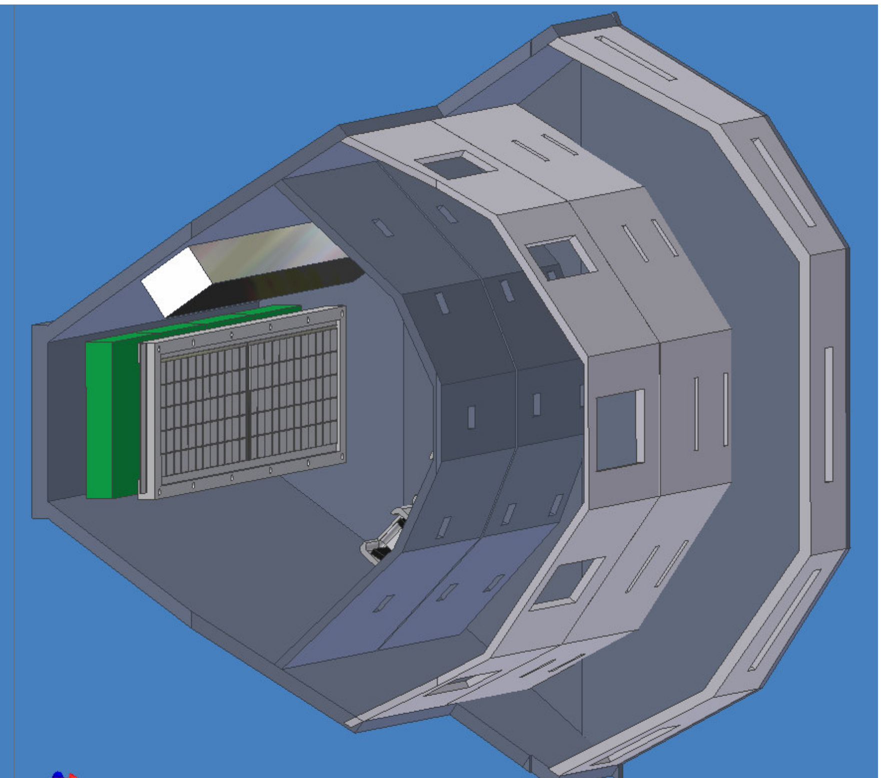
Proposed RBSP instrument


ESMI
ISCI
HEA


Radiation
Belt Distribution
Imager
NNH05ZDA003O
November 2005
NASA
TAYLOR
UNIVERSITY
Marshall Space
Flight Center
ITT Industries
Engineered for life

Pinhole Camera w/ multiple Pinholes

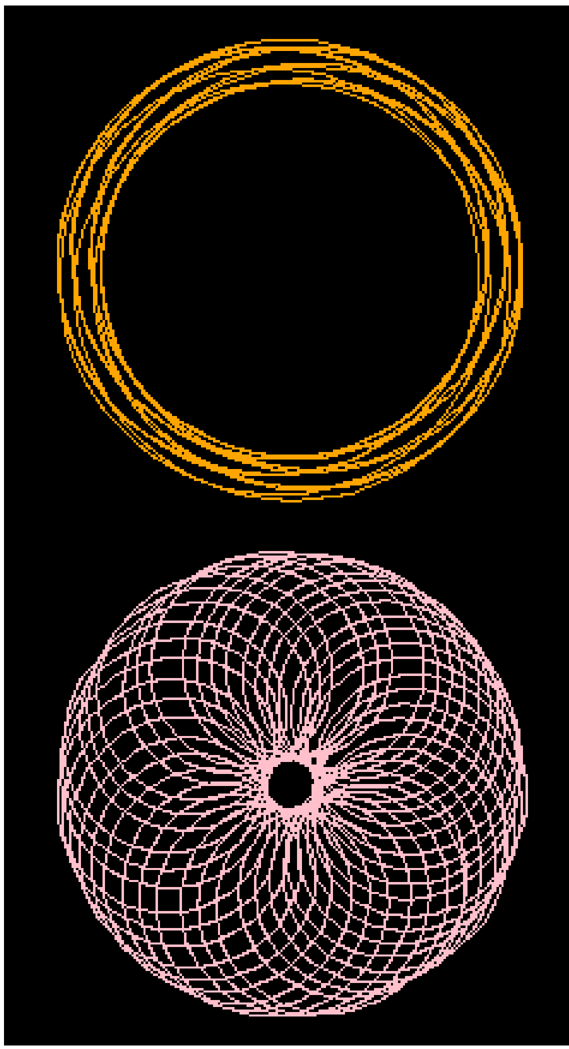




CONCLUSIONS

- The Outer Radiation Belt Electron conundrum will be solved by making new science measurements of high resolution energy, pitchangle, space and time
- This will enable ~24-48hr advance warning of MeV events.
- When combined with Solar warnings, this may become a week advance notice

Kolmogorov, Arnol'd, Moser (applied to Jupiter perturbation of Earth)



Earth orbit as Perturbed by Jupiter.

Poincaré slice x vs. v_X taken along the E-J line.

Earth orbit if Jupiter were 50k Earth masses.